Rolling Bearing Lubrication Technology Trends and R&D Efforts

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Lubrication technology for rolling bearings is an important elemental technology for providing sufficient bearing performance. It has been developed for the purpose of reducing friction and wear, providing longer bearing service life, reducing the amount of lubricant consumption, reducing environmentally burdening substances, etc. This report introduces trends regarding greases for rolling bearing used in main industrial fields and examples of research and development results related to lubrication technology achieved by JTEKT.

***Key Words**: lubrication technology, urea grease, long life, tribochemical reaction, extreme pressure additive*

1. Introduction

Rolling bearings are important mechanical elements that support rotating parts of machinery, and they are used in every industrial field including automobiles, electric appliances, information devices, steel mill equipment, railway cars, construction equipment, machine tools and aircrafts. In recent years, in accordance with the tendency that machines and equipment have been required to be more and more compact and lightweight with improved reliability and maintenance-free, rolling bearings have been operated in severer conditions and requirements have become more diversified. Moreover, it has become more important to meet such requirements as safety, global environmental protection, cost reduction and globalization. In these circumstances, technological development has been required on the lubrication technology, which is an important elemental technology to sustain satisfactory bearing performance, including development of lubricants and lubrication methods for reduction of friction and wear, extension of bearing life, lubricant consumption reduction and reduction of environmentally burdening substances.

This report introduces JTEKT recent research and development activities relating to bearing lubrication technology, including trends of rolling bearing greases in the main industrial fields. The development of long life greases, research results concerning tribological characteristics of additives, research and development results for environmentally friendly biodegradable grease and the development of polymer lubricants are also described in detail in this report.

2. Roles of Lubrication and Lubrication Technology in Rolling Bearing

In order that a rolling bearing performs satisfactorily, it is important to select proper lubricants and lubrication methods. Main roles of lubrication in a rolling bearing are reduction of friction and wear on the rolling and sliding surfaces, removal of frictional heat, extension of fatigue life by the formation of an appropriate oil film, protection from rusting and corrosion, and dust-proofing.

Lubrication method of rolling bearings is largely classified into grease lubrication and oil lubrication. And, in such special conditions as vacuum, high temperature, extremely low temperature, where neither grease nor oil can be used, solid lubricant and coating or transfer film are used for lubrication.

3. Trends of Rolling Bearing Greases in Main Industries

3. 1 Automobile Industry

Along with automobile manufacturers' efforts to improve fuel efficiency, to reduce exhaust gasses and to enhance safety/comfort, rolling bearings have been required to be more compact and lightweight with improved performance and reliability.

Hub unit bearing for automobile wheel application, in which bearing rings, shaft and housing are integrated, have been commonly used for the purpose of size and weight reduction, reliability improvement and simplicity of installation. While automobile wheel bearings have conventionally been lubricated by lithium soap greases, they have predominantly been replaced by urea base mineral oil type greases which excel in heat resistance, adhesion to friction surface, penetrability and lubricity in order to cope with bearing temperature rise due to installation of disc brake, maintenance-free requirement, and false brinelling occurring in transportation of vehicles on railways.

Bearings for engine auxiliary application such as alternators and air compressors for car air conditioners are used under vibration, high-speed and high temperature conditions. As for the alternators, compact and high power alternators with built-in IC regulator and rotor fan have become dominant[1]. Two grease-packed ball bearings are used to support the rotor. They initially suffered premature flaking accompanied by a microstructural change called white etching band (WEB). Development results regarding the grease developed for this problem will be given in detail in Section **6**.

3. 2 Industrial Equipment Fields

3. 2. 1 Wind Power Generation

As clean energy, wind power generation has been rapidly spreading not only in Germany and Denmark but all around the world.

The wind turbine generator is comprised of blades, rotor spindle, speed-up gear box, generators and yaw gear box, and incorporates many bearings. They are lubricated by grease except for the speed-up gear box bearings which are lubricated by oil. Since the wind turbines are often installed where the operating temperature condition is severe and/or where it is difficult to provide maintenance service, synthetic fluids or grease, which can be used over a wide temperature range and expect to be longer life, are widely used[2]. The grease for a rotor spindle bearing is required to provide low torque at low temperature, withstand loads, protect the bearing from rust and help extend the bearing life. The grease currently selected is lithium soap grease or lithium complex soap grease whose base oil is poly α olefin or mineral oil.

3. 2. 2 Steel Mills

Rolling bearings used in steel making equipment are exposed to very severe operating conditions such as high temperature, heavy loads, water and dust.

Roll neck bearings in hot and cold rolling mills are not only subject to heavy loads and impact loads, but also susceptible to intrusion of cooling water and scales around the rolls, resulting in such problems as softening grease or shorter bearing life. It is common to select lithium soap greases with excellent water resistance and load carrying capacity, or special lithium complex soap greases providing oil lubrication function with excellent PV performance. Recently, calcium sulfonate complex greases, which have excellent extreme pressure resistance, rust prevention, adhesiveness and shear stability, have been widely used.

In a continuous casting facility, guide roll bearings are operated at high temperature. Because of heavy loads at very slow speed, it is difficult to form a lubricating film, so the bearing is operated under boundary lubrication. The grease often used is urea grease with high viscosity base oil.

3. 2. 3 Railway Cars

Forty years have passed since the Tokaido Shinkansen bullet train started operation in 1964 in Japan. Since then, there have been active development efforts to make bullet trains faster, lighter with longer overhauling intervals.

In the traction motors for bullet trains, cylindrical roller bearings and ball bearings have been used with grease lubrication. In recent years, these traction motors have been switched from conventional DC motors to induction motors which have enabled higher speed operation as well as the extension of the overhauling intervals. This change has made the lubrication of the bearings more important. Originally, lithium soap grease with a mineral oil base had been used for the main motor bearings. In conjunction with the introduction of induction motors on the 300 series Nozomi trains, the bearing grease was changed to lithium complex soap grease with the mineral oil base to cope with higher speed and higher temperature. This grease has been employed in the new bullet trains as well as many other main motors.

The axle journal bearings for bullet trains have been either a combination of a double row cylindrical roller bearing and a ball bearing or a flanged double row cylindrical roller bearing with oil bath lubrication. In the 500 series Nozomi trains which started its commercial service at maximum speed of 300 km/h in 1997, a grease packed double row tapered roller bearing was used with the first adoption of a grease lubrication for bullet trains. Adoption of this bearing has not only facilitated the design of a compact and lightweight journal, but also enabled higher speed and maintenance-free operation. The lithium soap grease based on high viscosity index hydro-refined mineral oil, which has been successfully used in TGV and other high-speed trains in Europe, is used for the grease in this bearing.

3. 2. 4 Machine Tools

In order to improve productivity of machine tools, constant efforts have been made to allow their main spindles to run at higher speed with higher stiffness and higher accuracy. Recently, more emphasis has been placed on energy saving and environmental protection. For machine tool spindles, angular contact ball bearings or cylindrical roller bearings are used, though it has become usual to use ceramic rolling elements in the spindle bearings to accommodate higher spindle speeds.

While both oil-air lubrication and grease lubrication are mainly used for the spindle bearings, the expansion of application range of grease lubrication and raising of limiting speed are under consideration, for energy saving and environmental protection. JTEKT has developed a high-speed angular contact ball bearing (High Ability Bearings) for machine tools and accomplished successful operation at 1 730 000 dmn with lubrication by barium complex soap grease with a diester oil base[3].

3. 3 Electric & IT Equipment Fields

Electrically conductive grease that can provide rolling bearings with a conductive function is described.

The rolling bearings used on the photosensitive drums, transfer section and fixing section of PPC copiers and LBP printers are often required to have a conductive property in order to eliminate electrostatic charge. Thus, the needs for conductive bearings have been increasing. In order to make a bearing conductive, the bearing is filled with a grease containing carbon black. Poly α olefin is often used as the base oil taking account of a possible chemical attack on various resins such as polycarbonate resin and ABS resin used in these units. Recently needs for conductive bearings on the fixing unit (heat roller) have increased to avoid paper adhesion around the roller due to static charge. As the bearing in this unit is used at 180 ~ 250℃, a fluorinated grease including carbon black has been developed and successfully put into practical use.

4. Development of Long Life Urea Greases (KNG Greases)

To cope with the increase in temperature, rotational speed and load under which rolling bearings are operated, JTEKT started in the middle of 1970s (earlier than competitors), a development project of high performance and long life urea grease, which resulted in successfully developing KNG grease featuring low noise, high temperature, high speed and long life[4].

Urea grease is grease with chemical compound having a urea group (-NH-CO-NH-) as the thickener. It is classified into diurea, triurea and tetraurea, depending on the number of urea groups, as well as into aliphatic urea, aromatic urea and alicyclic urea, depending on the structure of the group end. Urea grease is commonly manufactured by chemical reaction of amine with isocyanate in the base oil. Depending on the kinds of amine and isocyanate, grease properties such as consistency, dropping point, shear stability and oxidation stability vary to a great extent. Therefore, the combination of these raw materials is important in developing urea grease.

Urea grease has the advantages, compared to soap base greases, having a higher dropping point, excellent heat resistance and oxidation stability, and longer service life at high temperature, whereas it has such drawbacks as thermo-hardening property, inferior shear stability and rust prevention, and noise due to large particles of thickener, which were technical problems to be solved in development of bearing grease.

In the development of KNG greases, therefore, we tried to keep such advantages of urea grease as excellent heat resistance and oxidation stability, while solving such technical problems as noise characteristics and rust prevention through the combination of raw materials and improvement in the grease manufacturing process. Such synthetic oil as poly α olefin and alkyldiphenylether with excellent heat resistance, oxidation stability and low temperature properties were selected as the base oil. In addition, to further improve performance, various heat-resistant additives were combined. As this grease is manufactured in a dedicated dust-free plant, where advanced particle refinement and uniformizing treatment is applied, it has excellent noise characteristics.

Various KNG greases have been developed to meet requirements depending on applications and operating conditions. Compositions and properties of representative KNG greases are shown in **Table 1**.

4. 1 KNG144

KNG144 is a wide temperature range, long life grease developed for low noise bearings used in various electric motors. It offers greater vibration damping effects than wide temperature range grease which is highly evaluated as low noise grease and doesn't cause such noise as commercial high temperature urea grease.

4. 2 KNG170

KNG170 was originally developed for high-speed alternator bearings offering excellent heat resistance and oxidation stability as well as extremely good shear stability. Moreover, KNG170 features high channeling property at high speed and allows low friction torque, low temperature rise, minimum hardening and leakage and long life. The base oil is poly α olefin.

As the grease for bearings in automobile electrical and engine auxiliary devices, KNG170 has been replaced by KNG250 grease developed to counter the white band flaking. However, KNG170 is still used for other high-temperature, high-speed applications.

4. 3 W191

W191 is the grease developed for automobile water pump bearings.

Along with the trend for smaller and lighter water pumps, water pump bearings have been required to withstand higher temperature and higher speed, while the increase of belt tension has put the bearing under heavier loads. Still, demand for longer life of water pump bearings has been strong. Moreover, water pump

Table 1 Compositions, properties and examples of use of KNG greases

		KNG144	KNG170	W191	KNG250
Thickener		Diurea	Diurea	Diurea	Diurea
Base oil		Poly α olefin mineral oil	Poly α olefin mineral oil	Poly α olefin mineral oil	Alkyldiphenylether
Kinematic viscosity of base oil, mm^2/s	40℃	54	56	135	97
	100℃	8	9	16	12
Worked penetration 25℃		246	242	275	238
Dropping point, ℃		250 min.	250 min.	250 min.	250 min.
Evaporation loss, mass% 99℃, 22 h		0.16	0.13	0.23	0.19
Oil separation, mass% 100℃, 24 h		0.3	0.5	0.7	0.4
Oxidation stability, kPa 99℃, 100 h		20	15	30	10
Worked stability 100 000 worked		298	294	334	315
Water washout, mass% 79℃, 1 h		1.3	1.0	1.3	0.8
Low temperature torque, mN・m −30℃	Starting torque	630	350	770	320
	Running torque	99	69	103	48
Operating temperature range, ℃		–30～130	–40～150	–30～130	–40～180

bearings are susceptible to the intrusion of coolant in liquid or water vapor state, even though protected by mechanical seal and high performance rubber seal. W191 is designed to ensure long life at high temperature and high-speed operation, as well as to improve load carrying capacity and shear stability in case of water intrusion into the bearing. It can provide three times longer life than conventional greases[5].

4. 4 KNG250

KNG250 was developed to solve the problem of white band flaking on bearings used for automobile electrical devices and engine auxiliary devices such as alternators, electro-magnetic clutches for air conditioners and belt tensioners. Details will be discussed in Section **6** below.

5. Study on Tribochemical Reaction and Tribological Properties of Extreme Pressure Additives

Lubricants and greases incorporate antioxidant, antirust and other additives to improve their performance. It has been known that organometallic extreme pressure additives, represented by the organic molybdenum compound, are effective to improve anti-wear and anti-friction characteristics in the boundary lubrication condition. The author et al. have discovered that these additives have the effect of preventing white band flaking[6].

Under boundary lubrication, an extreme pressure or anti-wear additive performs a tribochemical reaction on the friction surface and prevents seizure or wear by forming surface film of metal oxides or sulfides.

Here, friction and wear characteristics of organometallic extreme pressure additives, analysis of compositions and chemical structures of surface film formed by tribochemical reactions and research results of new additives are described.

5. 1 Wear and Friction Characteristics of Organometallic Extreme Pressure Additives

A series of wear/friction test was conducted on urea grease and lithium soap grease, both using alkyldiphenylether as the base oil, with various extreme pressure additives by using the reciprocating sliding friction tester (SRV tester).

Change of friction coefficient over time and the shape of friction surface of the disc after the test are shown in **Figs. 1** and **2**, respectively. Findings from these tests were: ① the urea grease has better wear/friction characteristics than the lithium soap grease; ② MoDTC and SbDTC have a friction reducing effect due to the film formed on the friction surface; though the variation of friction coefficient is larger because the film is not so strong, and; ③ ZnDTP showed a significant effect to prevent wear due to very tough film formed, though its effect for reducing friction is relatively low[7].

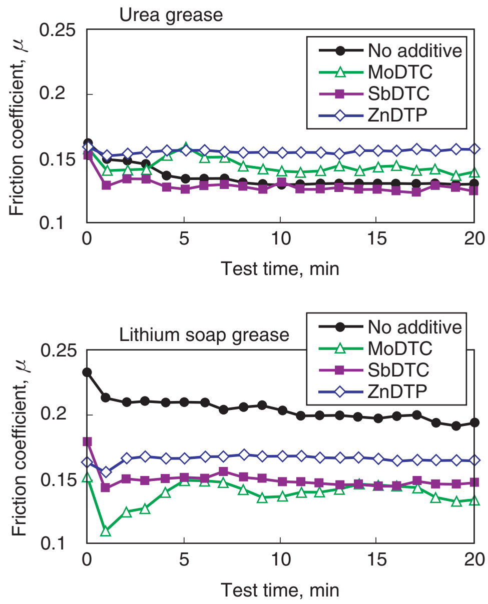

Fig. 1 Change of friction coefficient over time

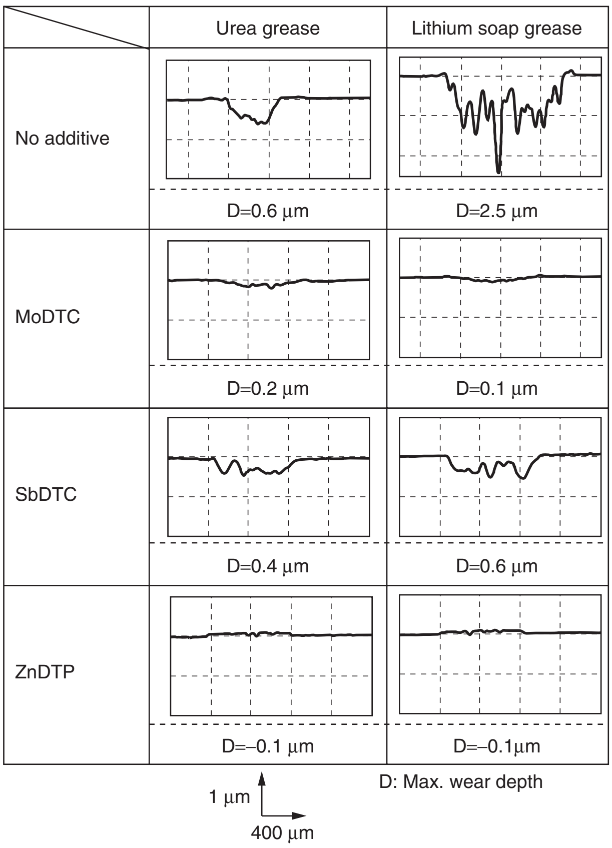

Fig. 2 Shape of friction surface after test

Furthermore, another test was conducted to determine improvement in wear/friction characteristics by mixed use of SbDTC and Zn based additives; i.e. the extreme pressure additive ZnDTC and the rust preventive Zn-sulfonate. Change of friction coefficient is shown in **Fig. 3**. As shown, not only combined use with ZnDTC but also with Zn-sulfonate showed an improvement effect[8].

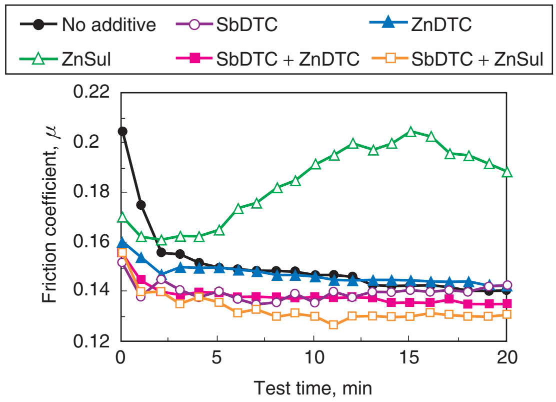

Fig. 3 Change of friction coefficient over time

5. 2 Analysis of Composition and Structure of Surface Film

The effects of extreme pressure additives or anti-wear additives are obtained by the surface film formed by tribochemical reaction. It is, therefore, important to identify the chemical structure and film thickness of the surface film formed on the friction surface. Therefore, the surface film was analyzed by using analysis methods such as EPMA, AES and XPS.

Figure 4 shows the appearance of the friction surface after the friction test, revealing the porphyritic formation of the surface film. **Figures 5** and **6** show the results of AES and XPS analysis. As previously shown, SbDTC was effective for reduction of friction and wear when used with a combination of Zn based additives. The top layer of the surface film was composed of oxide and sulfide of Sb, under which there was a subsurface layer of sulfide of Zn. It appears that the oxide and sulfide of Sb worked effectively to reduce the friction coefficient while the sulfide of Zn prevented wear[8].

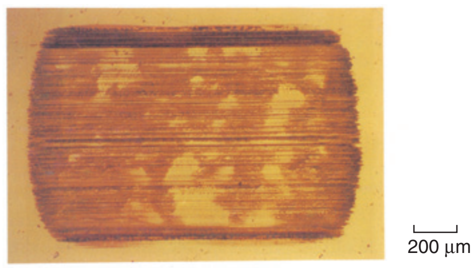

Fig. 4 Appearance of friction surface (SbDTC + Zn Sul)

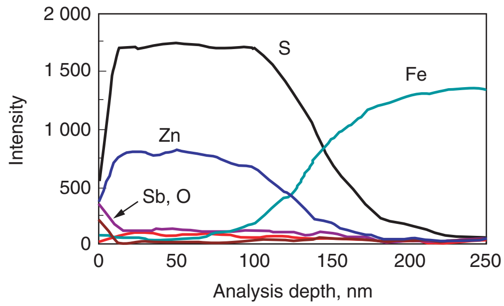

Fig. 5 Results of friction surface AES analysis (SbDTC + Zn Sul)

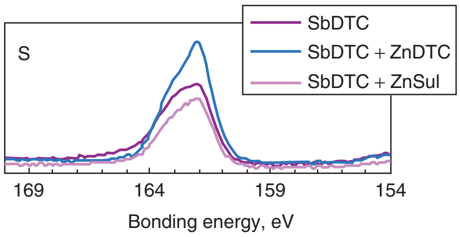

Fig. 6 Results of friction surface XPS analysis

In addition, a rotational test of a rolling bearing packed with the same grease was performed and the composition and structure of the surface film formed on the outer ring raceway was analyzed. The test bearing was a deep groove ball bearing with a 15mm bore diameter. The test was done at 9 000 ~ 18 000 min^{-1} at bearing temperature 100℃ under 2 kN radial load for 100 hours. After the test, the film formed on the outer ring raceway was analyzed. **Figure 7** shows the appearance of the film formed on the outer ring raceway, and **Fig. 8** shows the result of AES analysis. The analysis showed that the composition of the surface film formed by rolling contact was mainly oxides of Sb and Zn, which were different from that out of sliding contact prevailed by sulfide. This difference is considered to be attributable to the difference in friction conditions[9].

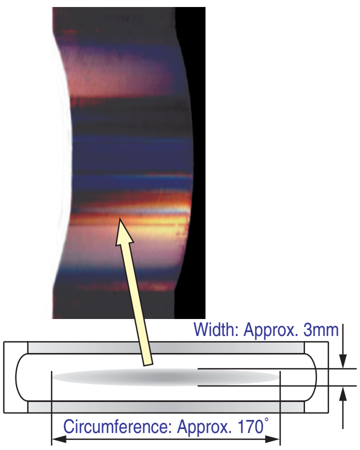

Fig. 7 Appearance of friction surface (SbDTC + Zn Sul)

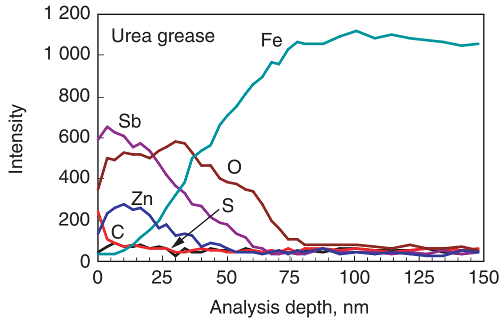

Fig. 8 Results of friction surface AES analysis (SbDTC + Zn Sul)

5. 3 Tribological Characteristics of Bismuth Type Extreme Pressure Additive

Bismuth is relatively less toxic among heavy elements, and its compound is used as an ingredient in lead-free soldering alloy. In a research report, it was expected that an organic bismuth compound could replace the lead-based extreme pressure additive[10]. Paying attention to this additive, JTEKT has studied the tribological characteristics of the bismuth compound, with a result that, as an extreme pressure additive, bismuth dithiocarbamate (BiDTC) is superior in load carrying capacity and heat resistance.

A sample of alkyldiphenylether with BiDTC as an additive was subjected to SRV tester to evaluate its wear/friction characteristics and formation of the surface film. **Figure 9** shows the change of friction coefficient over time with the samples added with various concentrations of additives. It was shown that BiDTC generates the surface film under sliding friction and has friction reducing effect. The film consisted of sulfide of Bi, and the lowest friction value was obtained with 7 500 ppm of Bi concentration[11].

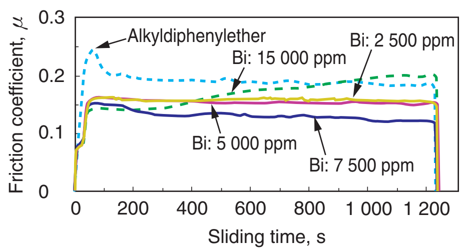

Fig. 9 Change of friction coefficient over time (BiDTC)

6. Development of Anti-White-Band-Flaking Grease

Bearings used in automobile electrical devices and engine auxiliary parts, such as alternators, electro-magnetic clutches for air conditioners and tensioners, encountered the problem of early flaking accompanied by microstructural change of the steel on the fixed ring raceway (outer ring in case of the inner ring rotation). It was related to the increase of bearing speeds and operating temperatures due to smaller size, lighter weight and higher performance of these devices, as well as to increased bearing load and vibration due to increased belt tension and stiffness in conjunction with the adoption of V-ribbed belts. For alternators, two grease-packed ball bearings are used to support the rotor. The bearing maximum speed is 18 000 min^{-1} and the maximum operating temperature is around 130℃. Flaking on the outer ring of the bearing, unlike the ordinary flaking experienced so far, was characterized by a subsurface layer which showed a whitened microstructure when it is nital etched (hence, it is called white band flaking). Concerning the mechanism by which the white band flaking occurs, some theories attributing it to impact loading or hydrogen brittleness were reported. On the other hand, JTEKT went through a series of reproduction tests and microstructural analysis and suggested that the main cause was the increased internal stress due to sliding, high contact pressure, impact load and vibration, while the flaking could be promoted by the hydrogen which is generated by disintegration of the grease and water on the contact area between the rolling element and the raceway, which intrudes into steel. Based on this estimation of the flaking generation mechanism, the strategy established to contain the problem included the reduction of impact load by oil film, the reduction of friction by surface film of additive, and the containment of generation of hydrogen and its intrusion into the steel. To this end, grease of diurea grease based on alkyldiphenylether (ADE) with an organometallic extreme pressure additive was developed[6). This additive successfully formed the surface film by tribochemical reaction in the operating bearing, which proved effective to reduce the impact stress as well as the rolling stress in addition to suppressing the generation of hydrogen and its intrusion into the steel. Thus, it showed the substantial effect to prevent white band flaking from occurring and thereby extend the bearing life. The properties of the developed grease KNG250 are shown in **Table 1**.

7. R&D for Vegetable Oil Based Biodegradable Grease

Because the lubricating oil and grease in the bearings used in outdoor use machinery such as construction and agricultural machinery can, if they leak out, pollute the environment, affecting the ecology of flora and fauna, the use of biodegradable lubricant is increasing. **Figure 10** shows the result of biodegradability test in accordance with OECD301C modified MITI method. As shown, vegetable oil and ester have by far greater biodegradability than mineral oil or poly α olefin. Biodegradable lubricants based on vegetable oils or fatty acid ester have been commercialized[12)]. On the other hand, vegetable oil made from such resource crops as rapeseed and soybean can be continuously and are expected to become more important as the alternative for fossil resource-based lubricants for solving environmental problems and establishing a sustainable society.

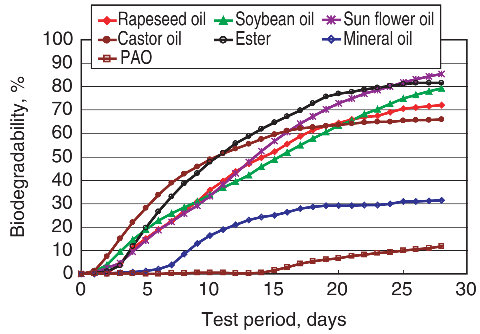

Fig. 10 Result of biodegradation test

There have not been many application examples of biodegradable grease for rolling bearings. Currently, vegetable oil based biodegradable greases available for industrial use are inferior in heat resistance and lubrication life, hence useful for limited bearing applications. Therefore JTEKT has set out a project to study tribological characteristics, grease life improvement and development of products[13) ~ 16)]. First of all, to improve grease life, an investigation was conducted on the process of grease deterioration and the effect of antioxidants[13)]. In a life test of vegetable oil base grease, gelling of the grease caused the bearing temperature rise, resulting in bearing life. As a result of grease analysis after the test, it was found that the amount of high molecular compound increased with the test time, which suggested that gelling was caused by the formation of high polymerization and cross linking within and between molecules in the vicinity of unsaturated bonds in the base oil. In addition, ten antioxidants including amines, phenols and quinolines were evaluated for their effects in rapeseed oil based calcium soap grease. Change of the total acid number in a thin film heating test and the results of grease life tests are shown in **Figs. 11** and **12**, respectively. It was found that the quinoline antioxidant is effective in prevention of oxidation and deterioration of grease as well as in lubrication life enhancement. Based on these test results, a new biodegradable long life grease called "BIOSUPER LL Grease" (**Fig. 13**), which has a five times longer life than the conventional vegetable oil based biodegradable grease, has been developed. This new grease has been certified as an eco-marked product.

Table 2 shows typical properties of the BIOSUPER LL. The OECD biodegradability test resulted in 84% degradation after 28 days[17)]. This grease is recommended for bearings used in construction and agricultural machinery as well as in ground maintenance equipment.

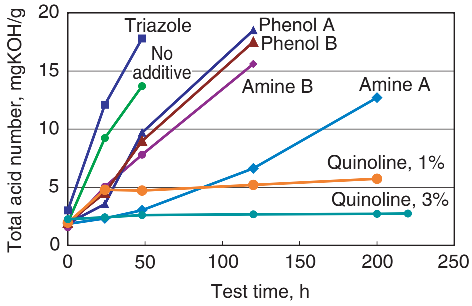

Fig. 11 Change of total acid number in thin film heating test

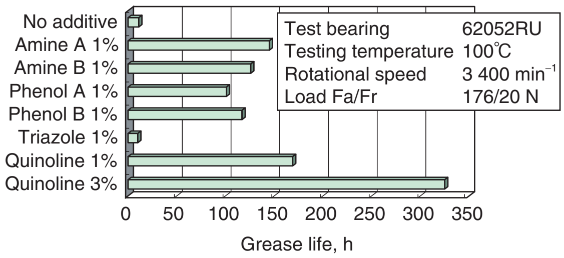

Fig. 12 Result of grease life test

Fig. 13 BIOSUPER LL grease

Table 2 Composition and properties of BIOSUPER LL

Items			Representative value
Composition	Thickener		Calcium soap
	Base oil		Rapeseed oil
	Viscosity of base oil mm^2/s	40℃	34.9
		100℃	8.0
Appearance			Brown, buttery
Worked penetration		25℃	280
Dropping point, ℃			150
Oil separation, mass%	80℃, 24 h		1.5
	100h, 24 h		3.0
Oxidation stability, kPa	80℃, 100 h		33

8. Development of Polymer Lubricant Packed Bearings

The polymer lubricant is a solidified lubricant made by impregnating oil or grease in a resin such as polyethylene. Unlike the solid lubricant as MoS_2 and graphite, the resin serves only as a carrier of oil and lubrication is carried out by oil. Also, unlike the conventional oil impregnated plastics, the polymer lubricant is characterized by its capacity of carrying as much oil as 50% or more.

The polymer lubricants are often provided by a process of mixing fine powder of ultra high-molecular polyethylene resin with mineral oil or synthetic oil, followed by heating and solidification. As the resin has a fine porous structure, it retains the oil. The oil retained in this porous structure is bled out of the surface either when it is compressed or deformed under the load acting on it, when, at high temperature, expansion of oil differs from that of the resin, or when bearing rotation generates centrifugal force. The oil once bled out is reabsorbed into the porous structure by the capillary phenomenon and retained therein.

Bearings with polymer lubricant developed by JTEKT (SOLPACK Bearing) have an operating temperature range of –15 to 80℃, and a limiting speed of 35×10^4 dmn for ball bearings[6), 18)]. Currently this bearing is used in agricultural machinery and various transfer equipment in steel mills. Also, needle roller bearings incorporating polymer lubricant have been applied to the suspension mechanism of motorcycles.

9. Conclusion

As the technological revolution progresses, increased performance and functionality are required of rolling bearings. Research and development of lubrication technology that leads to higher functionality and cost effectiveness, while considering environmental protection and safety, is becoming more important. That is why the development of high reliability lubrication technology that is backed up by theoretical analysis is considered to be important.

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