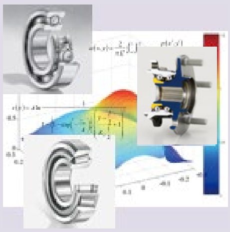
New Technology of Rolling Bearings Contributing to Low Fuel Consumption of Automobiles



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To reduce the fuel consumption of automobiles, rolling bearings are required to be lighter, smaller and have lower torque. Additionally, for electric automobiles, the rolling bearings that are used at high speed rotation and prevent electrolytic corrosion are also required.

In this paper, the technologies for these requirements are explained from the viewpoints of lubrication, numerical analysis, and materials.

1. Introduction

Recently, development of automobiles is drastically shifting from the conventional vehicles with an engine as the power source to hybrid vehicles (HEV and PHEV), which combine the engine and motor, fuel cell vehicles (FCV) and electric vehicles (BEV) which are driven only by motor. One of the reasons for this trend is the stricter global regulations on fuel consumption originated from environmental issues such as air pollution and global warming. Emphasis on reduction of CO_2 emissions while driving vehicles continues and enhanced regulations on fuel consumption take effect in Japan, the U.S., Europe and China toward 2021. Therefore, auto manufacturers and automotive component manufacturers are racing to introduce new technologies successively into the global market. On the other hand, engines are also used in HEVs and PHEVs; therefore, improvement of fuel/electricity efficiency is a critical challenge, too.

Based on the above situation, this article introduces “new technologies contributing to low fuel consumption of vehicles” with rolling bearings.

2. Challenges of Rolling Bearings Regarding Low Fuel Consumption

Approximately 100 to 150 bearings are used in a vehicle and rolling bearings are some of the components required for safe and comfortable driving. Rolling bearings are used in many parts of a vehicle, such as engine peripheral, transmission, various motors as accessories and driving axle units. There are broadly two characteristics for reducing fuel consumption of conventional vehicles powered by engines. One is lower torque and the other is compactness and lightweight for reducing the vehicle weight.

The requirements for rolling bearings toward electrification of vehicles include high-speed technology to support high-speed rotation of motors and avoidance of electrical corrosion in the vehicles with complex electrical current paths.

There may be other technological challenges specific to HEVs and PHEVs, as well as to FCVs and BEVs, but the main challenges overall are (1) lower torque, (2) compactness and lightweight, (3) high-speed rotation and (4) avoidance of electrical corrosion, which are inherent from electrification.

The following are the topics of the discussion in this article on those challenges:

(1) Lower torque: While grease lubricated rolling bearings are frequently used in vehicles, improvement of grease technology made a significant contribution to reducing torque. This article will discuss those cases.

(2) Compactness/lightweight: Technologies discussed in the past article[1] for improvement of materials/thermal treatments are making a good track record of results for contributing to compactness/lightweight. This article discusses improvement of bearing load carrying capacity by numerical analysis.

(3) High-speed rotation: High-speed rotation is usually supported by ball bearings and an accurate understanding of cage transformation in high-speed rotation is required. In this article, some cases of numerical analysis are discussed.

(4) Avoidance of electrical corrosion: While insulating film may be applied on the outer diameter of the raceway, this article discusses about ceramic ball bearings which are expected to provide highly reliable insulation capability and significant weight reduction.

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3. Lower Torque

Reduction of torque is required to grease lubricated rolling bearings from the viewpoint of energy efficiency and resource conservation. Reducing viscosity of grease base oil can reduce torque. However, a simple reduction of viscosity is not effective as it degrades the oil film formation and increases the risk of reduced bearing life. The following is an introduction of bearing torque reduction technology based on rheology characteristics of grease[2].

3.1 Relation of State of Existence of Grease Within Ball Bearings and Bearing Torque

The state of existence of grease within ball bearings can be broadly divided into a churning state where grease churning continues and torque is high and a channeling state where most grease is squeezed out from the rolling elements and torque is low. To observe the difference between those states, the condition of grease adhesion inside the bearing was investigated using X-ray CT, which is becoming a standard method for observing grease behavior.

Inner/outer rings, balls, cage and seals made of resin were used for the bearing to be observed, so that X-ray can be transmitted. For a better contrast between the grease and the other materials, 5% tungsten (by weight) was added in the grease as a tracer. As shown in **Fig. 1**, state of existence of grease between the balls and cage pocket was observed running the grease lubricated bearing while torque is measured. In the initial stage (after 5 hours of operation) where the bearing was stopped in the churning state (torque: 13 Nmm) and when the bearing was assumed to reach the channeling state after a long hours (23 hours) of operation (torque: 5 Nmm). It revealed that there was a large difference in the amount of grease between the balls and the cage pockets between the two states, as shown in **Fig. 2**.

<Resin-made bearing torque measurement condition>
6204, 25 °C, Fa=19.6 N, 3,600 min^{-1}

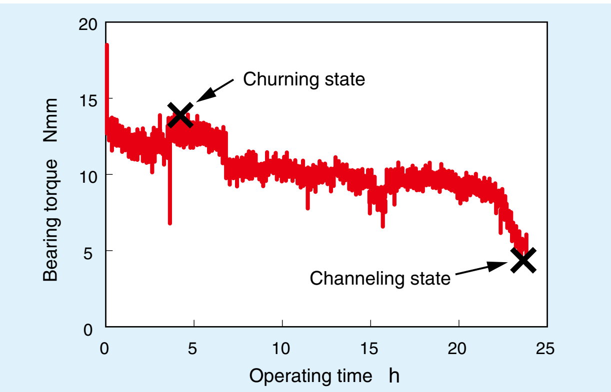
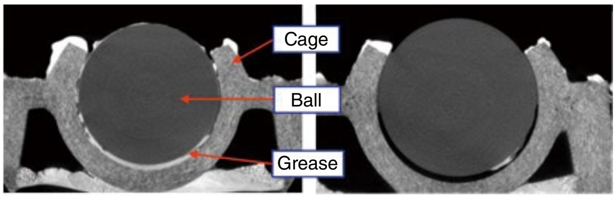


Fig. 1 Chronological change of bearing torque of resin made bearing



Churning state (Torque: 13 Nmm) Channeling state (Torque: 5 Nmm)

Fig. 2 State of grease adhesion in resin made bearing (between ball and cage pocket surface)

3.2 Basic Concept of Lowering Torque by Grease

The observation of X-ray CT revealed that shear stress of grease between the balls and the cage pocket surface needs to be reduced in order to reduce torque in grease lubrication. That is, two points, namely, 1) reduction of grease viscosity and 2) faster transition to channeling state, are effective. The following is an example of verification of these effects by using 4 types (grease A to D) of grease for rolling bearings **(Table 1)**.

Table 1 Sample grease

		Grease A	Grease B	Grease C	Grease D
Thickener		Lithium soap	Urea	Urea	Urea
Base oil	Type	Synthetic oil	Synthetic oil	Synthetic oil	Mineral oil
	Kinematic viscosity mm^2/s (40°C)	25	40	23	95
Consistency		250	250	280	290

1) Reduction of Grease Viscosity

Grease viscosity is a function of grease shear velocity, therefore viscosity needs to be reduced in the shear velocity zone between the balls and the cage pocket surface under the operating condition of rolling bearings. If the balls are assumed to be at the center of the cage pockets and the inner ring of a ball bearing (6204) rotates at 1,800-10,000 min^{-1}, then the grease shear velocity of the cage pocket is 24,000-130,000 s^{-1}.

Fig. 3 shows the relation between the shear stress at the cage pocket obtained by calculating the actual grease viscosity measured with a rheometer multiplied by the shear velocity, and the bearing torque actually measured at the initial stage of operation. Except for grease D at 1,800 min^{-1}, the more the shear stress, the greater the bearing torque in all the conditions (any grease types and rotational speeds). Reduction of grease viscosity at the shear velocity equivalent to the cage pockets and reduction of shear stress between the balls and the cage pocket surface are effective for reducing torque.

2) Faster Transition to Channeling State

In grease lubrication, the difference between the churning state and channeling state has a major impact on bearing torque. For low torque, the channeling state, where the grease between the balls and the cage pocket surface is quickly squeezed out, is more desirable. Grease D at 1,800 min^{-1} in **Fig. 3** is considered to be in the channeling state and the other conditions are considered to be in the churning state.

By changing angle of oscillation with the rheometer, the storage modulus G', which indicates grease property as solid, and the loss modulus G', which indicates the grease property as liquid, are measured and the shear stress, where the ratio of those two ($tan\ \delta$ = G" /G') is 1, is obtained as the yield stress **(Fig. 4).** As shown in **Fig. 5**, it was verified that the grease with high yield stress (grease C and D) can transition from the churning state (high torque) to the channeling state (low torque) within the operating time of 120 min., the grease with low yield stress (grease A and B) cannot transition to the channeling state (low torque).

The grease in the bearing with a rotating inner ring moves from the raceway surface to the inner diameter of the outer ring by the centrifugal force and stays there as agglomeration. It is assumed that the agglomerated grease or oil separated from it flows back to the raceway lubricating the bearing[3]. As shown in **Fig. 6**, it is considered that the grease agglomerated on the inner diameter of the outer ring with higher yield stress is harder to move to the raceway surface by vibration and temperature rise, allowing more stable channeling state.

<Bearing torque measurement condition>
6204, 25 °C, Fa=19.6 N, 1,800-10,000 min^{-1}

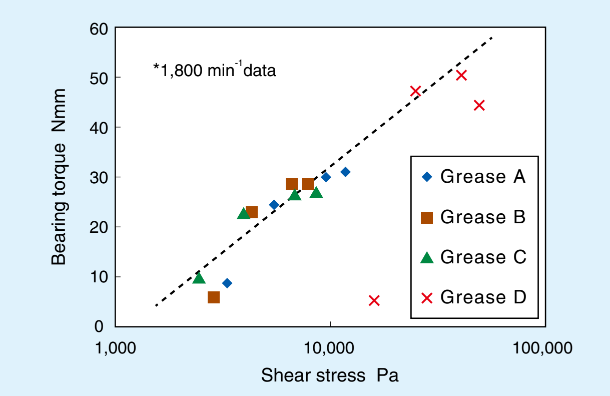


Fig. 3 Relationship between bearing torque and cage pocket shear stress

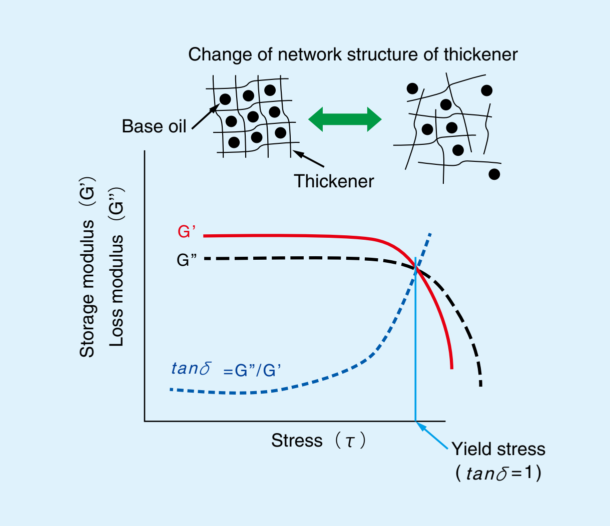


Fig. 4 Example of measurement of yield stress by rheometer

<Bearing torque measurement condition>
6204, 25 °C, Fa=19.6 N, 1,800 min^{-1}

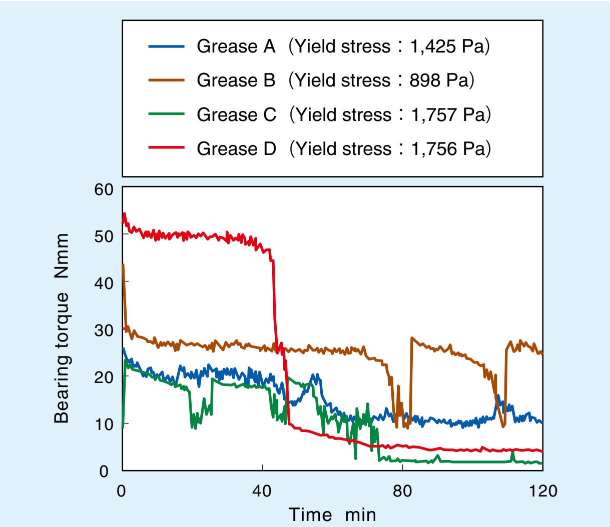


Fig. 5 Relationship between grease yield stress and bearing torque

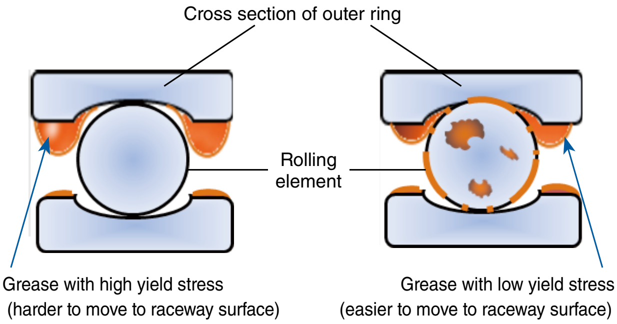


Fig. 6 Schematic diagram of grease flow agglomerated on the inner diameter of outer ring

3.3 Application to Grease for Hub Bearings

NTN is developing different types of grease for various applications based on the low torque technologies by grease described in 3.2. As an example, the case of application of the grease for hub bearings, which has particularly strong demand for low torque among automotive components[4] is introduced.

In this development, reduction of grease shear stress between the raceway and rolling elements is also elaborated in addition to the reduction of the grease shear stress between the balls and cage pocket surface.

(1) Reduction of Grease Shear Stress Between the Balls and Cage Pocket Surface

Fig. 7 and **8** show the comparison of the grease viscosity and yield stress between the conventional product and the developed product. The developed product provides lower viscosity and higher yield stress in the shear velocity zone above 2,000 s^{-1}, which is important in hub bearings, than the conventional product, as a result of elaboration on grease composition. Control of these physical properties made it possible to reduce grease shear stress between the balls and cage pocket surface and achieve low torque.

<Grease viscosity measurement condition>
Cone-plate rheometer, 25°C, 1 ⇒ 8,000 s^{-1}, steady flow

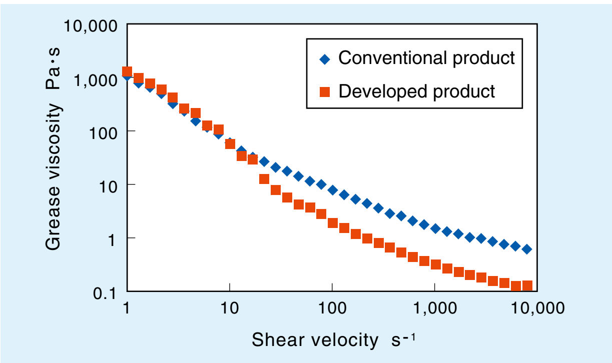


Fig. 7 Relationship between shear velocity and grease viscosity

<Yield stress measurement condition>
Parallel plate rheometer, 25°C, 1 Hz, 10 ⇒ 3,000 Pa

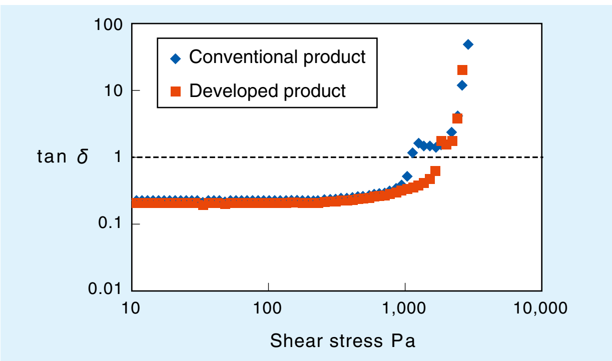


Fig. 8 Measurement result of yield stress

(2) Reduction of Grease Shear Stress Between Raceway and Rolling Elements

With ball bearings, it is known that the small sliding between the raceway and the rolling elements, which is called differential slips and spins, cause friction (traction)[5]. **Fig. 9** shows the investigation result of the impact of the molecular structure of grease composition on the traction. It was revealed that the traction can be reduced by reducing circular/branching structure in the molecular structure of the base oil and making the straight-chain structure as the dominant structure. The developed product improved the molecular structure in addition to the rheology property of the grease for achieving torque reduction.

<Traction measurement condition>
25°C, 0.65 GPa, 0.2 ⇒ 1.0 m/s (3% slip)

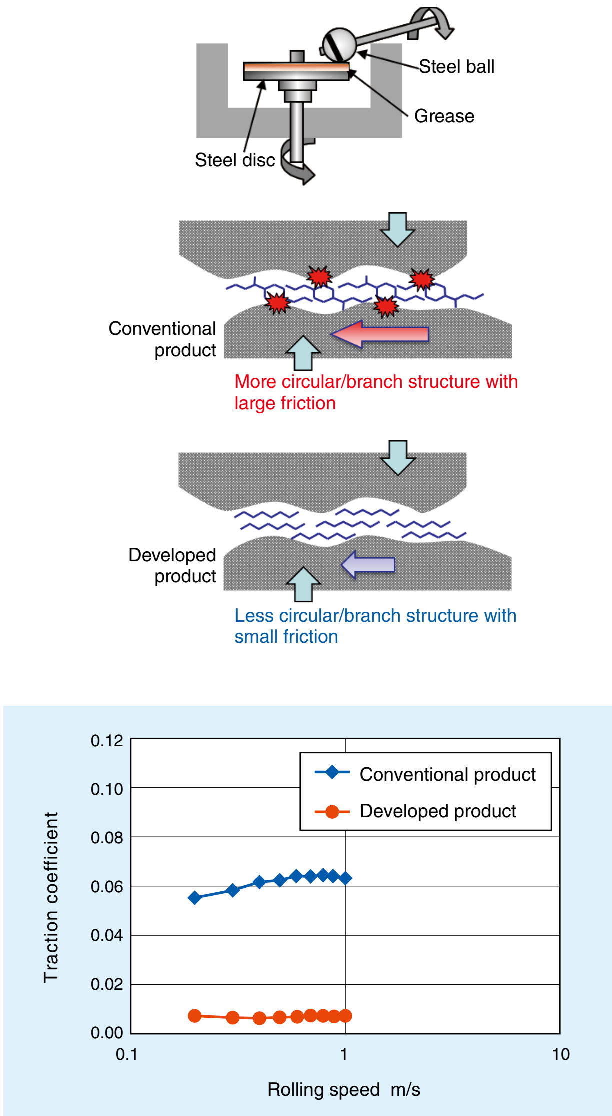


Fig. 9 Relationship between molecular structure of grease component and traction

4. Compactness/lightweight

For low fuel consumption, it is necessary to reduce the size and weight of each individual component of a vehicle. In case of rolling bearings, a simple downsizing causes reduction of system life. Therefore, past efforts were focused on the improvement of material to reduce the size while maintaining the required system life[1]. In this article, a technology for long system life is introduced, with a new viewpoint of changing the design of the bearing internal shape, which contributes to downsizing.

The rolling element and raceway are in line contact as they are basically cylinders; however, if they are made of simple cylinders, excessive stress is concentrated on both ends of the contact called "edge load." Therefore, the radii of both ends of the rolling elements and raceway are reduced by a few μ m, called "crowning." Edge loading can be prevented by applying large crowning even in the misaligned condition; however, that causes large maximum stress at the center of the roller, causing reduction of operating life. Although the theoretical shape to minimize the maximum stress while preventing the edge load was known to be a logarithmic curve, the ideal curve could not be actually processed and the impact of misalignment, which is realistically unavoidable could not be eliminated. **NTN** developed a proprietary logarithmic function formula for crowning with improved degree of design freedom, as well as an automated design method using mathematical optimization method[6].

Fig. 10 shows a diagram of the distribution of stress. The logarithmic crowning reduces the edge stress even if the amount of processing at the edges is almost the same as the conventional crowning, resulting in longer operating life. By using this technology, compact and light bearings can be developed maintaining equivalent life as the conventional products, which contribute to lower torque and lower fuel consumption.

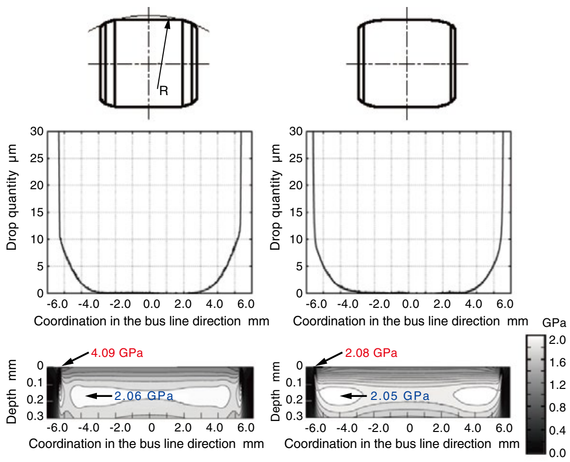


Fig. 10 Crowning geometry and distribution of Mises equivalent stresses[7]

5. High-speed Rotation

The motor, as the power source of an EV, becomes larger if designed with the low speed/high torque specification; therefore, it is designed with the high speed/ low torque specification for compactness and the required torque is created by reducing the speed. This requires the rolling bearings for EV motors to support high-speed rotation.

The type of bearings suitable for high-speed operation is ball bearings. Resin made cages, which exhibit superior self-lubricating property, are frequently used to reduce friction loss. An ordinary resin-made cage has a shape asymmetric with respect to the axial direction called a "snap cage," as shown in **Fig. 11**. The pocket has an open end in the axial direction where a ball is snapped in. The claws on the open end of the pocket can open to the outer diameter side when operated in high speed, by the centrifugal force, as shown in **Fig. 12**, with deformation like flower petals. This type of deformation of claws can interfere with the balls and outer ring, causing an increased friction loss and wear.

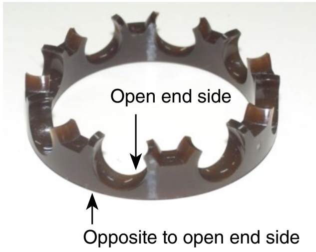


Fig. 11 Resin made snap cage

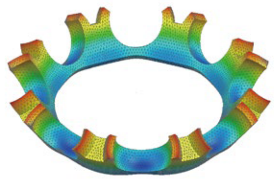
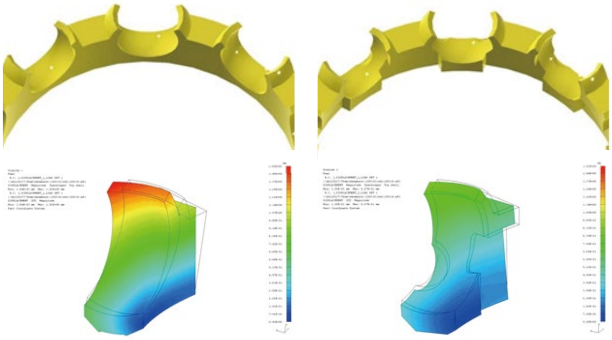


Fig. 12 Example of deformation analysis of resin made snap cage

Therefore, the thickness of the claw portion was reduced for lightweight and the rigidity of the ring portion on the opposite side of the open end was reduced to allow deformation of the ring to the outer diameter direction, to decrease the impact of the deformation of the claws. **Fig. 13** shows the deformation of the cages of the conventional structure and the developed product in high-speed rotation. In the case of the snap cage, the limitation of the high-speed rotation is not in the cage strength but in the local deformation of the claws. Noticing this fact, the challenge was solved not by providing high rigidity to prevent deformation but conversely, by making the entire piece a flexible structure. For example, the permitted rotational speed of oil lubricated 6206 is 13,000 min^{-1}; however, adoption of this technology achieved a normal operation of 17,000 min^{-1}.



(a) Conventional cage (b) Developed cage

Fig. 13 Example of deformation analysis due to centrifugal force and cage shape

Even higher speed can be achieved by adopting a cage that prevents deformation of the pocket and its surrounding by integrating axially divided components snapped into one[8].

6. Avoidance of Electrical Corrosion

While insulating film made by resin or ceramics may be applied on the outer diameter of the raceway for preventing electrical corrosion of rolling bearings, this article discusses about ceramic balls which are expected to provide highly reliable insulation capability and significant weight reduction.

A type of damages incurred to the bearings used in motors and generators is called electrical corrosion. The electrical corrosion is a phenomenon of damage on the rolling surface by sparks generated at the rolling contact by the electrical current that flows into the bearing. The metallographic structure is deteriorated by the spark generated at the rolling contacts, resulting in vibration, noise and flaking.

Devices equipped with motors, for instance, use carbon brushes for grounding the shaft or shut down the electrical current from the bearings by shaft insulator, etc. However, each of them has issues in durability, such as wear of carbon brushes during operation and thermal degradation of resin, if resin insulator is used for shutting down the electrical current. As a method to solve these issues, a hybrid bearing, where ceramic balls made of silicon nitride are incorporated in the raceway made of steel, is effective.

To verify the insulation capability of the hybrid bearing with the ceramic balls made of silicon nitride, a bearing peel life test was conducted under current carrying condition using direct current, as an example. **Fig. 14** shows an outline of the test equipment. This test equipment supports the rotational shaft by the bearing under the test and a support bearing. The housing is divided into 2 parts by the insulation. The electrical current flows from the terminal A → bearing under test → rotational shaft → support bearing → terminal B when the terminal A and B are activated. **Table 2** shows the test condition. The test was conducted by applying a constant current (0.5 A) under quick acceleration condition guided by the inner ring (in case of the bearing with ceramic balls made of silicon nitride, the applied voltage was set to 30 V). **Table 3** shows the test results.

As shown in **Table 3**, the ceramic balls made of silicon nitride can contain peeling of rolling element surface due to electrical corrosion, since they are insulating body, compared to the steel balls. Therefore, the ceramic balls made of silicon nitride with insulation capability are expected to be used in the bearings of various types of motors used in the next generation vehicles, which will be widely adopted such as HEVs, PHEVs and EVs.

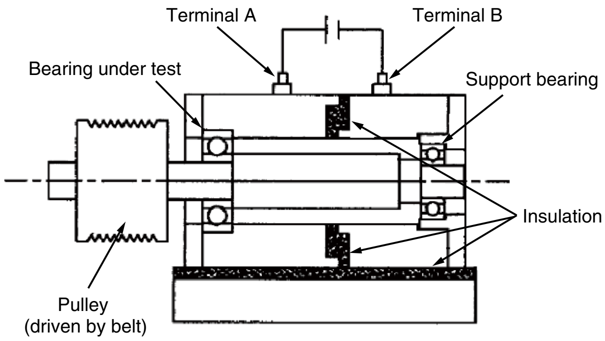


Fig. 14 Peeling life tester under current carrying condition

Table 2 Test condition

Bearing under test	Deep groove ball bearing (6203)	
Rolling element	Steel ball	Ceramic ball
Grease	Nonconductive grease	
Amount of injected grease (g)	0.86	
Rotational speed (min^{-1})	Quick acceleration/ deceleration from 0 to 20,000	
Atmosphere	Room temperature	
Pulley load (N)	1,617	
Bearing load (N)	2,332	
Current (A)	0.5	–
Stopping condition	When the vibration is 10 times than initial condition	

Table 3 Peeling life test results

	Life (h)	Peeling region
Steel ball	19.6	Ball
Ceramic ball	> 200	None

In addition to the solution for avoidance of electrical corrosion, ceramic balls are also effective for reducing weight. The specific gravity of the ceramic made of silicon nitride is around 40% of the bearing steel; therefore, applying ceramic balls made of silicon nitride for rolling elements makes the bearing lighter than an ordinary bearing with the raceway and rolling elements made of bearing steel (SUJ2). In addition, lighter rolling elements contribute to reduction of centrifugal force applied to the rolling elements during rotation of the bearing, which helps support the increasing demand of higher speed motors for HEVs, PHEVs and EVs.

In case of deep groove ball bearing 6206, applying ceramic balls made of silicon nitride for rolling elements makes the hybrid bearing lighter than the ordinary bearing with the raceway and rolling elements made of bearing steel (SUJ2) by approx. 10%. As shown in **Fig. 15**, applying ceramic balls made of silicon nitride for hub bearings reduced the weight by approx. 13%, contributing to low fuel consumption of vehicles.

Fig. 15 1st generation hub bearing (using ceramic balls)

In addition, ceramic made of silicon nitride is chemically stable which is expected to help reduce oxidative deterioration of lubricant between the raceway made of bearing steel and the rolling elements and improve anti-galling property by avoiding adhesion if the rolling elements made of bearing steel are replaced with the ceramic made of silicon nitride.

The seizure resistance property was evaluated in the combination of steel ball (SUJ2) and ceramic ball made of silicon nitride (Si3N4) using a four-ball friction tester. The test condition is shown in **Table 4** and the test result is shown in **Fig. 16**. Four-ball friction testing uses three fixed balls on which a rolling ball rotates. Seizure resistance property was evaluated by running the tester for a minute at a constant load and when the friction coefficient did not increase, the load was increased. The test was stopped when the friction coefficient rose more than 5 times the initial condition when the seizure occurred. As shown in **Fig. 16**, a combination of steel balls and a ceramic ball made of silicon nitride indicated the best seizure resistance property.

Since seizure resistance property improves when steel is used for inner/outer rings and ceramic made of silicon nitride is used for rolling elements, low fuel consumption of vehicles can be expected by reduced use of lubricant and therefore, low torque effect.

Table 4 Test condition

Test equipment	Four-ball friction tester
Material of balls under test	Steel ball (SUJ2), ceramic ball (Si3N4)
Ball size (inch)	3/4
Lubricating oil	Turbine oil grade 68
Lubricating condition	Dipping
Atmosphere	Room temperature
Slide velocity (m/s)	0.86
Stopping condition	When the friction coefficient rose more than 5 times from the initial condition

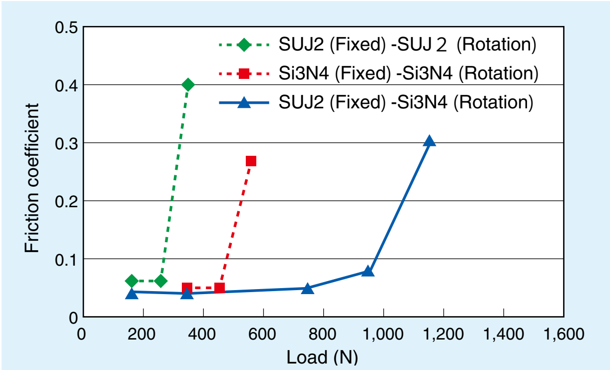


Fig. 16 Seizure resistance test result

7. Conclusion

New technologies contributing to low fuel consumption of vehicles, such as design technology by numerical analysis for rolling bearings, weight reduction technologies and low torque technologies were discussed. The hope is these new technologies help support measures against the environmental issues such as global warming and global tendency of fuel cost increase.

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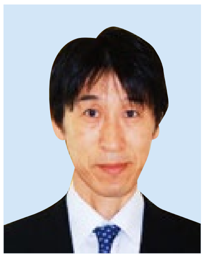

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