Progress and Prospect of Technologies for Rolling Bearings[*1]

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Rolling bearings are mechanical elements that guide the rotation while supporting the load by rolling motion of rolling elements. They are used for supporting the rotating shaft of various industrial machines and contribute to reduction of energy consumption and heat generation by reducing friction, suppression of wear and prevention of seizure. Rolling bearings have been improved in reliability and high performance by the evolution of materials and tribology technology. In this report, the progress and future prospect of rolling bearing technology is described, focusing on the birth and evolution of tapered roller bearings which has played a major role in the development of the automobile industry, taking examples of life improvement technology by material and heat treatment and friction reduction technology.

Key Words: *rolling bearings, tribology, material, heat treatment, friction torque, tapered roller bearings*

1. Introduction

Rolling bearings[1)] are mechanical elements that guide rotation while supporting a load with the rolling motion of components called "rolling elements". Rolling bearings are used for supporting the rotating shaft of various industrial machines and contribute to the reduction of energy consumption and heat generation through the reduction of friction, suppression of wear, prevention of seizure, etc. Referred to in Japan as the "rice of the industry", the rolling bearings that support modern industrialized society have improved reliability and high performance due to the evolution of materials and tribology technology[2-4)]. In particular, strong ties exist between rolling bearings and automobiles, which are indispensable to modern-day life, and it would not be an overstatement to say that the history of technologies for rolling bearings is equivalent to the history of bearings used in automobiles[5-7)].

This report focuses on the birth and evolution of the tapered roller bearing[1, 8, 9)] which has, amongst the various types of rolling bearings, played a particularly major part in the advancement of the automotive industry, and discusses the progress and prospect of technologies for rolling bearings by presenting technologies to improve life through material and heat treatment and technologies to reduce friction[10)].

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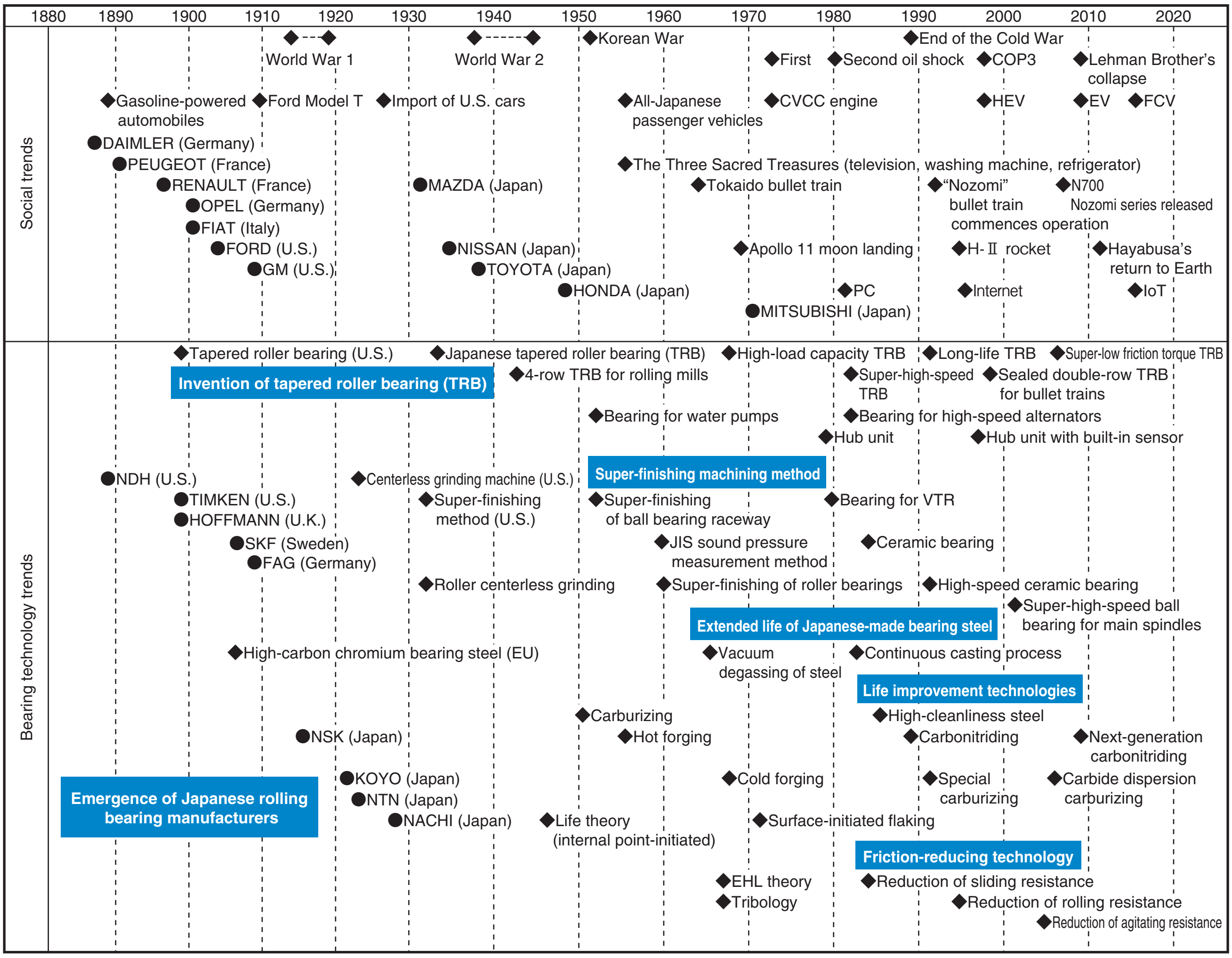
2. The Birth and Evolution of Rolling Bearings

2. 1 The birth of rolling bearings

Since ancient times, humans have needed to carry heavy objects. Examples of rolling motion being used to reduce friction in ancient times include the adoption of vehicles with wheels in around 3000 BC and "rolling sleds" in around 700 BC, wherein logs were utilized as sleds[11)]. From the late 15th century to the 16th century, Leonardo da Vinci began research into rolling friction and conceived the original form of modern-day rolling bearings[5)]. Rolling bearings advanced notably during the Industrial Revolution (around 1750 to 1850), with Valro[11)] proposing ball bearings for use in the axles of horse-drawn carriages in 1772 and Garnett[11)] patenting a roller bearing for axles in 1787.

Kakuta provides a detailed review of the history of the rolling bearing industry[12)]. **Table 1** shows the birth and development of the rolling bearing industry prepared by referring to Kakuta's review. A large quantity of rolling bearings actually began being used in the late 19th century, and rolling bearing manufacturers were established primarily in Europe and the U.S. This coincided with the establishment of European and American automotive manufacturers. The advancement in machine tools and improvement in grinding technologies of the Industrial Revolution made it possible to mass produce high-accuracy bearings and this led to their dramatic increase in popularity.

Table 1 History of birth and development of rolling bearing industry[12)]



2. 2 Ball bearings

Bicycles were the driving force behind the significant advancement in ball bearings. Initially, sliding bearings were used in bicycles, however in 1862, a bicycle equipped with ball bearings was invented and this is said to have reduced bicycle friction from between one-fifth and one-tenth as well as increased maximum speed[11)]. With the spread of ball bearings, a need arose for the manufacture of high-accuracy, high-strength steel balls and in 1898, HOFFMANN established a steel ball manufacturing company; making it possible to manufacture balls with good accuracy. In the beginning of the 20th century, HOFFMANN grew as a manufacturer of high-accuracy ball bearings.

2. 3 Tapered roller bearing

Just as bicycles were the driving force behind the advancement of ball bearings, horse-drawn carriages, followed by automobiles, were the driving forces behind the advancement of tapered roller bearings. Tapered roller bearings were invented in the U.S. at the end of the 19th century for use in axles of horse-drawn carriages. The ball bearings that were used in axles at the time were susceptible to breakage. In 1898, TIMKEN[13)], which was already operating a successful carriage business, obtained a U.S. patent[5)] for an assembly comprising an integrated axle and tapered roller bearing. This invention made it possible to easily support the load created when the carriage was turning or travelling on an uneven surface at the same time as enabling adjustment of bearing wear through the tightening of nuts at the end of the axle, hence reducing both static and dynamic friction of the vehicle by 25 to 50%[11)].

At the beginning of the 20th century, tapered roller bearings began being adopted on the axles of automobiles. The Model T Ford, which was released in 1908, mass produced and became immensely popular, adopted the tapered roller bearing on its undercarriage. As a result of repeated improvements to support both the large radial load and axial load created when turning a vehicle, in 1924, a shape and structure[13)] of the tapered roller bearing virtually the same as the one used today was created and contributed to the development of automobiles.

2. 4 Evolution of Japan's rolling bearing technology[14)]

From the mid-1910s, Japan's major rolling bearing manufacturers began establishing one after the next. This was a period of armament expansion in accordance with the Post-WW1 policy of increasing national prosperity and military power however another major factor was demand from the private sector such as an increase in the number of imported automobiles[15)]. The quality of Japanese-made bearings at the time was not on par with that of imported rolling bearings and this state continued until after the Second World War.

In 1952, under the guidance of the Ministry of International Trade and Industry's Machinery Laboratory, four major Japanese bearing manufacturers succeeded in jointly developing the super-finishing machining method and this provided the opportunity for a dramatic improvement in the machining accuracy of Japan's rolling bearings. On a global scale, Japan was producing rolling bearings with a surface roughness of a µm level or less in the 1950s, a relatively early stage for the rolling bearing field. In 1960, JIS (Japan Industrial Standard) was established relating to a method for measuring the sound level of rolling bearings[6)]. In this way, Japan's rolling bearings became increasingly low-vibration and low-noise.

Moreover, although the problem of Japanese bearings having a shorter life than Swedish bearings was identified from before WW2, Japan succeeded in reducing the oxygen content in steel by applying vacuum degassing and, with the introduction of continuous casting technology in the 1980s, high-cleanliness bearings with an oxygen content of approx. 5 ppm were realized[16)]. With the reduction of oxide inclusions, the life of Japanese bearing steel increased by around 30 times that of atmospheric-welded steel[16)], making it longer than the life of Swedish steel.

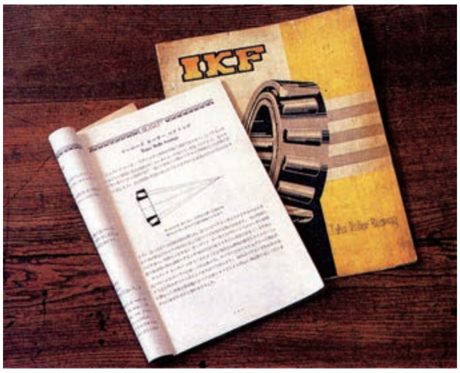


Fig. 1 Pamphlet of tapered roller bearings[15)]

2. 5 Shift to domestic production of tapered roller bearings and technological progress[15)]

Japan's full-scale production of tapered roller bearings began in 1933. Around this time, there was a rapid increase in imported cars, and a huge demand for bearings for use in repair work had emerged. **Figure 1** shows a pamphlet for tapered roller bearings from that time. A major contributing factor to this mass production was the development of production technologies, such as the application of centerless grinders to roller grinding[17)]. At the time, it was said that only TIMKEN was capable of producing tapered roller bearings, so this advancement surprised and attracted the attention of not only bearing customers but also industry in general. Around the same time as tapered roller bearings began being made domestically, Japan's major automotive manufacturers began emerging one after the next. In 1943, Japan also succeeded in the domestic production[18)] of large 4-row tapered roller bearings for rolling mill roll necks of domestic steel-making equipment.

After WW2, carburizing and quenching technology was established in 1950 and the production of thin tapered roller bearings using case-hardened steel[19)] became possible. The introduction of cold forging in 1968 enabled the production of high-load capacity tapered roller bearings[20)] able to withstand high loads despite being compact and thin. Compared to conventional hot forging, the forging ratio was dramatically improved with cold forging, and bearings had strength, were particularly superior in terms of toughness, and were able to be made thin enough to sufficiently respond to weight-reduction needs. Furthermore, it became possible to omit the turning process due to being able to obtain forged parts of extremely high accuracy. Due to the improvement in quality and productivity in accordance with these technologies, it became possible to respond to issues such as an increase in demand and extension in life of bearings for automobiles.

3. Life Improvement Technologies with Material and Heat Treatment

The bearing ring and rolling element of rolling bearings need to be capable of withstanding a high contact stress up to several GPa in localized areas, therefore are required to have sufficient strength, rolling fatigue life and the functions of high wear resistance, good dimensional accuracy and so on. In order to respond to such requirements, selecting the right material and optimal heat treatment are important and efforts were made including improving the quality of general high-carbon chrome bearing steel SUJ2, improving heat treatment methods and conditions, applying case hardening bearing steel, etc. Damage caused by rolling fatigue is called "flaking" and the state of damage differs depending on operating environment and conditions. **Figure 2** shows the modes of flaking and mechanisms[8] while **Fig. 3** shows the concept and countermeasures for life improvement[21] of bearings used in clean lubricant and contaminated lubricant containing foreign matter such as wear debris. The below introduces life improvement technologies for flaking initiated from surface, which has particular stringent requirements for automotive applications, such as differential gears and transmissions.

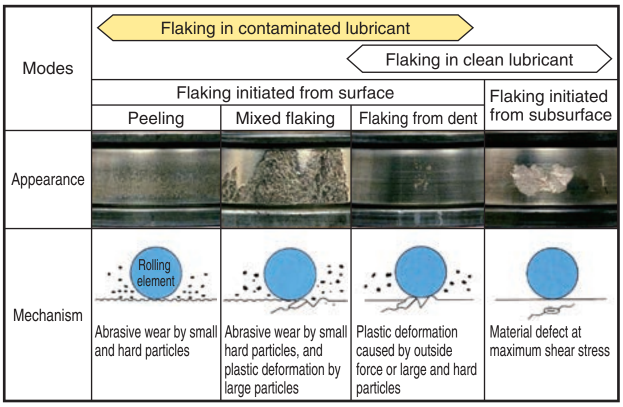


Fig. 2 Types of flaking and mechanism[8]

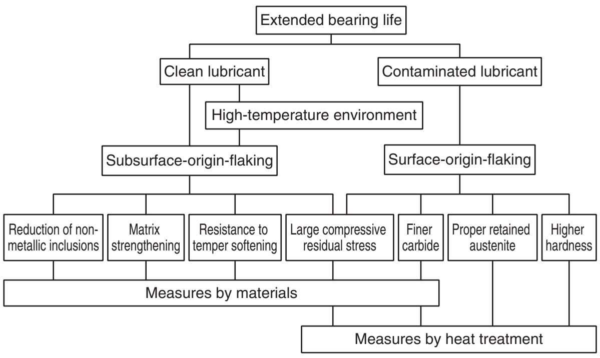


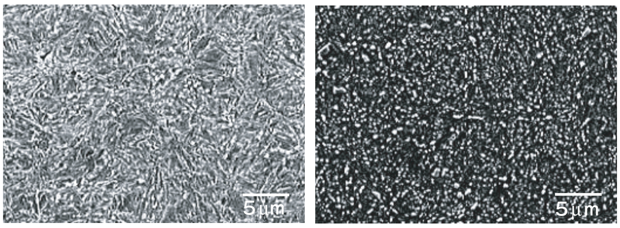
Fig. 3 Life improvement and countermeasure by material and heat treatment[21]

As **Fig. 2** shows, surface flaking easily occurs if there are small, hard foreign particles contained in the lubricant and can be considered close to abrasive wear. As countermeasures for this type of wear, hardening the surface and increasing the carbon content of the material base are effective. Flaking from dent occurs when large, hard foreign particles become caught in the rolling face and create indentations, causing stress to become concentrated when the rolling element travels past the raised section on the edge of the indentation. Effective countermeasures for this mode of flaking are hardening the surface and increasing the residual austenite (hereinafter γ_R).

Table 2 shows improvement technologies of rolling bearing life by improving material and heat treatment[21-26]. Against the above-mentioned flaking initiated from surface, carbonitriding[23] and special carburizing heat treatment[24] are able to extend life. Other technologies proposed to further extend life are carbide dispersion carburizing technology which enables both high surface hardness and increased γ_R through[25] precipitation strengthening of microscopic carbides (**Fig. 4**), and a new carbonitriding technology to increase γ_R without

Table 2 Improvement technologies of rolling bearing life by improving material and heat treatment

Developed/proposed technology	Feature (material structure-related feature)	Development target		Life ratio (standard bearing ratio)	
		Material	Heat treatment	In clean lubricant	In contaminated lubricant
High-cleanliness steel[22] (1985)	Long-life comparable to special-welded steel Inclusion control	Bearing steel	Through hardening	Over 3 times	Equivalent
Carbonitriding[23] (1989)	High hardness, creation of compressive residual stress Increased γ_R	Bearing steel	Carbonitriding	Over 3 times	Over 6 times
Special carburizing[24] (1992)	High hardness γ_R appropriation	Case hardening bearing steel	Special carburizing	Over 2 times	Over 10 times
Carbide dispersion carburizing[25] (2004)	High hardness, increased γ_R Increased fine precipitation	Case hardening bearing steel	Carbide dispersion carburizing	Over 4 times	Over 15 times
Next-generation carbonitriding[26] (2009)	High hardness, creation of compressive residual stress Ultra-increased γ_R Increased fine alloy precipitation	Bearing steel	Carbonitriding	Over 4 times	Over 8 times



(a) Conventional carburized bearing (b) Developed carbide dispersion carburized bearing

Fig. 4 Comparison of microstructure after heat treatment

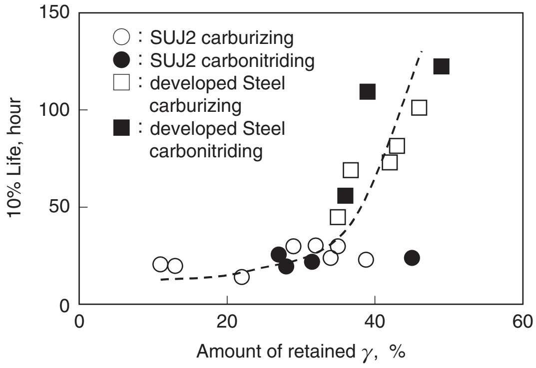


Fig. 5 Relationship between amount of retained γ and L_{10} life[3)]

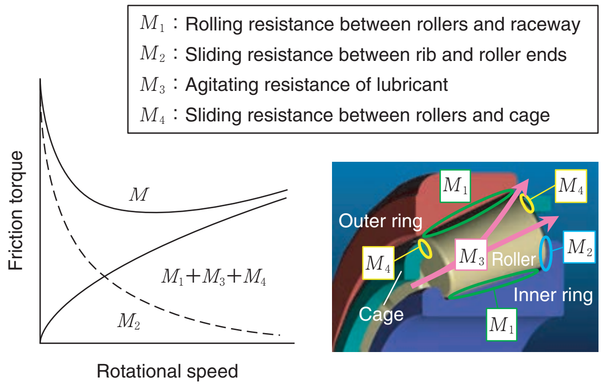


Fig. 6 Friction torque of tapered roller bearing[27)]

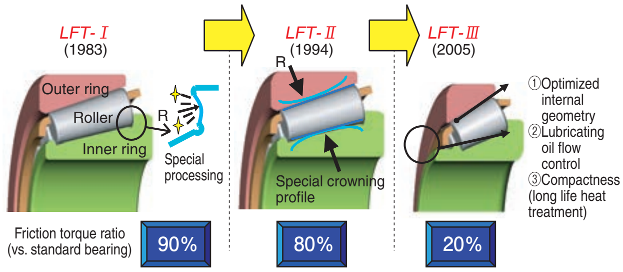


Fig. 7 Transition of low friction torque tapered roller bearing[10)]

reducing hardness through appropriation of alloying precipitation[26)]. As **Fig. 5** shows, life is remarkably improved by significantly increasing the γ_R while maintaining hardness. These technologies can contribute to the downsizing and lightening of machine components which make up automobiles and industrial machinery, as well as improving the reliability of such components.

4. Technologies for Reducing Friction

Tapered roller bearings have a large load capacity of around 2 to 2.5 times greater than ball bearings, which have the same space volume. Moreover, tapered roller bearings are resilient against impact load and have high rigidity, making them able to support rotating axes in a more compact structure than ball bearings. For this reason, tapered roller bearings are used in the drivetrain systems of automobiles such as differential gears and transmissions, as well as all types of industrial machinery, including steel rolling mills, construction machinery and railway carriages. However, generally-speaking, tapered roller bearings have higher friction and generate greater heat compared to ball bearings. **Figure 6** shows the causes of friction torque in tapered roller bearings[27)]. In low-speed zones where the formation of lubricant film is insufficient, the sliding friction resistance between the large inner ring rib (hereinafter "rib") and large roller end face (hereinafter "roller end face") is dominant, while in high-speed zones where the lubricant film is formed and fluid lubrication is achieved, the viscous rolling resistance between the rollers and raceway, as well as the lubricant agitating resistance are dominant.

Reduction of bearing friction torque, or in other words, realization of low friction torque, leads to increased efficiency of machinery and equipment as well as reduced energy loss, which in turn greatly contributes to reducing environmental load. As such, achieving low friction torque tapered roller bearings is considered equally as important as extending bearing life, therefore many engineers have worked to resolve this issue from down through history[28-39)] , and, as a result, the first low friction torque (LFT) tapered roller bearing was introduced on the market over 30 years ago. **Figure 7** shows the transition and structural technologies of LFT tapered roller bearings.

For the first generation LFT tapered roller bearing (LFT-Ⅰ)[33)], the rib was subjected to special processing, then, as shown in **Fig. 8**, the bearing was given a profile and roughness after the surface had sufficiently been established therefore making it possible to both reduce contact pressure and increase lubricant film formation performance, which ultimately resulted in reducing the sliding friction resistance between the rib and roller end face (M_2).

For the second generation (LFT-Ⅱ)[34)], by adding a special crowning profile to the inner and outer ring raceways, the rolling contact area between the rollers and raceway was reduced, which in turn reduces the viscous rolling resistance[35, 36)] caused by elasto-hydrodynamic

Bearing / Rib	Conventional	LFT
Profile	Tapered face	Special curved face
Roughness	Normal	Good

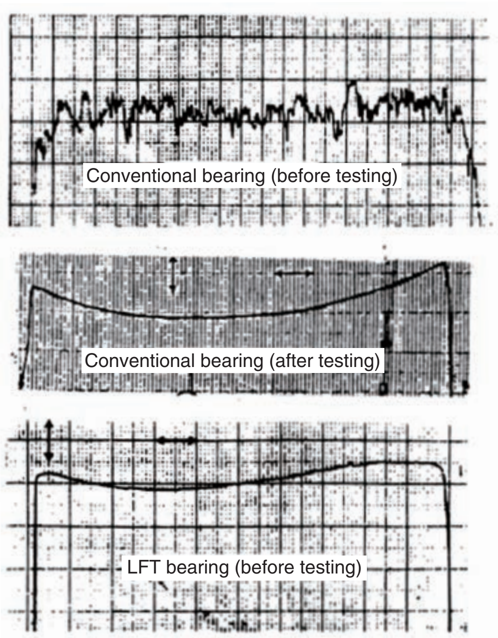


Fig. 8 Profile and roughness of inner rib face of tapered roller bearing[33)]

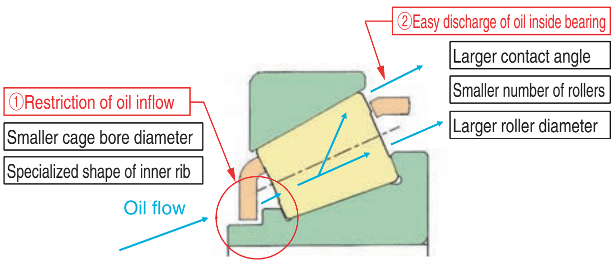
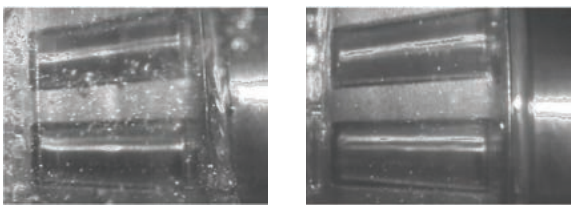


Fig. 9 Lubricating oil flow control for reduction of agitating resistance[9)]



(a) Conventional bearing (b) Developed bearing

Fig. 10 Observation of oil flow in tapered roller bearing[39)]

lubrication (EHL) (M_1).

For the third generation (LFT-Ⅲ)[37-39)], various internal geometry was optimized compared to the second generation, such as the number, length, diameter of the rollers and contact angle. This achieved a good balance between bearing life and rigidity and further reduced M_1. Simultaneously, lubricant was considered a bearing structural component, and agitating resistance (M_3) was reduced by suppressing lubricant flow, as shown in **Fig. 9** and **Fig. 10**. Furthermore, by reducing bearing size while maintaining life through the application of the aforementioned life improving technologies[24)], it was possible to further reduce M_1 and M_3. The third generation LFT tapered roller bearings are the same size as standard bearings, yet are able to reduce torque by 50% (or 80% if the downsizing effect is included)[39)], are therefore greatly contributing to reducing environmental load through energy conservation of vehicles.

As discussed above, the friction reduction technologies for tapered roller bearings area also being used for friction reduction in deep-groove ball bearings[40)], needle roller bearings[41)], hub units[42)] etc. Furthermore, ball bearings are often used with grease sealed into them, therefore low friction torque is achieved through the reduction of grease agitating resistance[43)] and seal sliding friction resistance[44)].

5. Prospects

Moving forward, the demand for rolling bearings to contribute to energy conservation through compactness, weight reduction and lower friction torque will continue to intensify. It is preferable that the life improvement technologies achieving size and weight reduction transition from developments combining material and heat treatment, to developments primarily focused on heat treatment. In order to realize this, it is important that further research is made into the impact of various alloying elements on bearing life and the associated mechanism, as well as identifying the alloying elements essential for improving bearing life and those alloying elements that can be substituted with heat treatment[3)].

In terms of achieving low friction torque, the key technologies are reduction and control of friction caused by lubricant viscosity. In order to realize this, the following is essential; further reduction of lubricant, low-viscosity lubricant and the design technology to achieve this, materials effective in reducing friction, improving wear resistance and improving anti-seizure performance, surface improvement and texturing technologies. In recent years, studies have been conducted to change cage profile in order to further reduce lubricant amount[45)] however in order to make this happen, it would be necessary to use resin for the cage and achieve good anti-seizure performance. As a means of solving these issues,

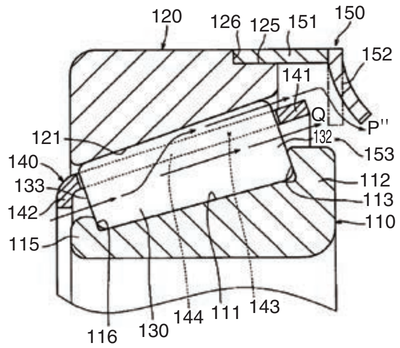


Fig. 11 Tapered roller bearing compatible with extremely small amount lubrication[46)]

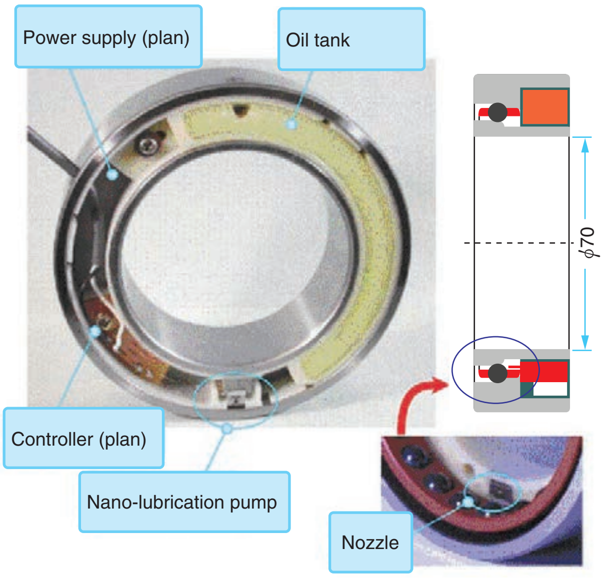


Fig. 12 Nano lubrication bearing with lubrication device[49)]

as shown in **Fig. 11**[46)] for example, a technology has been conceived wherein the lubricant guided to the outer ring side by centrifugal force is guided to the rib, which is susceptible to seizure. This technology reduces supply lubricant by 2%[47)] and is also believed to be effective in lowering the viscosity of lubricant. Furthermore, in the area of general rolling bearings, it is predicted that response to maintenance-free, IoT (Internet of Things) and IoE (Internet of Everything) will accelerate further due to the autonomous evolution of rolling bearings.

As one example, **Fig. 12** shows the nano-lubrication bearing[48, 49)] currently under-development for the practical realization of machine tool spindles. By having a lubricant unit built into the bearing, it is possible to supply an extremely small amount of lubricant when and where necessary therefore, compared to oil/air lubrication, which is the mainstream lubrication method for high-speed spindles, there are expectations that this will lead to simplification of the spindle structure, size reduction of machinery and equipment, suppression of oil mist, noise reduction, etc. Moreover, technology to equip sensors and transceivers enabling the real-time monitoring of operational status for large bearings[50)] is developed, which are extremely costly to replace, such as main spindle bearings of wind turbines, and initiatives for the practical realization of such technology is advancing.

6. Conclusion

The birth of rolling bearings and progress of related technologies, in particular Japan's rolling bearing technologies from post-WW2 to present-day, was introducing using the examples of technologies to achieve long life and low friction in the tapered roller bearing, which has played a major role in the advancement of the automotive industry. We hope that, through this report, you have gained a sense that the rolling bearings of today exist because of great effort and hardship on behalf of our predecessors and are the backbone of modern-day industrial society. We will continue to evolve rolling bearings, which most people are not normally aware of, as a strong and important element in the background.

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