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Next-generation half-toroidal CVT

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Development of the Next-Generation Toroidal CVT —Geared Neutral and Power-Split System for 450 N·m Engines—

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Technology Development Division-Headquarters

ABSTRACT

The world's first vehicle with a half-toroidal CVT (POWERTOROS Unit) has been manufactured since November 1999. In recent years, demands for a next-generation half-toroidal CVT that provides better fuel economy and ease of assembly and mounting have been growing in response to global environmental issues. The authors developed a new half-toroidal CVT that offers a wider ratio range, a more compact size, higher torque capacity, and higher efficiency. Major features of this new half-toroidal CVT include a geared-neutral system and power-split system. We mounted both systems to a test vehicle equipped with a 4.3L V8 gasoline engine, and demonstrated the effectiveness of our unique control concept for accelerating the vehicle from a stop, and mode changing between low-and high-speed driving. Bench test results and an evaluation of the driver's operation and performance feel of the vehicle are also reported.

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1. Introduction

In November 1999, the world's first traction-drive type half-toroidal Continuously Variable Transmission (CVT), which was integrated with NSK's POWERTOROS unit, was introduced to the Japan market in a luxury passenger car series.[1), 2), 3)] The smooth performance and responsive handling of the car had proven so popular that the half-toroidal CVT was made available in a sports sedan in February 2002.

In the 21st century, global environmental issues pertaining to the impact made by motor vehicles have forced the automotive industry to meet fuel economy standards that have become increasingly rigorous with each passing year. In response to these needs, the half-toroidal CVT was redesigned for greater compactness, improved efficiency, higher torque capacity, and all this at a lower cost. The authors have developed a next-generation half-toroidal CVT (Fig. 1) that adopts a geared-neutral and power-split system,[4)] which can help the automotive industry meet the strict demands placed on them. Developmental concepts of the next-generation half-toroidal CVT are as follows:

(1) More compact size for easier installation in a motor vehicle
(2) Improved efficiency for greater fuel economy
(3) Higher torque capacity for large-size passenger vehicles
(4) Simplified design for lowering assembly costs

In this paper, we will discuss developments already achieved for the half-toroidal CVT that are currently in the marketplace, and introduce basic components of our next-generation half-toroidal CVT. Afterwards, we will explain the features and structure of the next-generation CVT, and report on results of verification testing using an actual motor vehicle. Finally, we will discuss handling and responsiveness based on the driver's impression and other measured results.

2. Current Problems

The size, performance, and cost of a half-toroidal CVT are often compared with those of automatic transmissions (ATs). In order to achieve further compactness, greater efficiency, higher torque capacity, and lower cost, we focused our efforts on a number of developmental concepts, which are discussed here.

2.1 High torque capacity and size of transmission

2.1.1 Variator shape

(1) Toroidal cavity diameter: Current vehicles equipped with a half-toroidal CVT utilize a torque converter as a starting device. Since the load of a variator, which is used to attain a maximum speed ratio, is increased by the torque-amplifying action of the torque converter, it was difficult to reduce the half-toroidal cavity diameter because of the maximum input torque.
(2) Loading cam mechanism: A loading cam mechanism is a highly reliable device that can be used to control clamping force without an external unit. However, it was difficult for the loading cam mechanism to perform optimum clamping force in relation to change speed ratios and oil temperature. The challenge we faced was an excessive clamping force on the low end and the high end of the variator ratio. This factor also determined the large size of the conventional half-toroidal CVT.

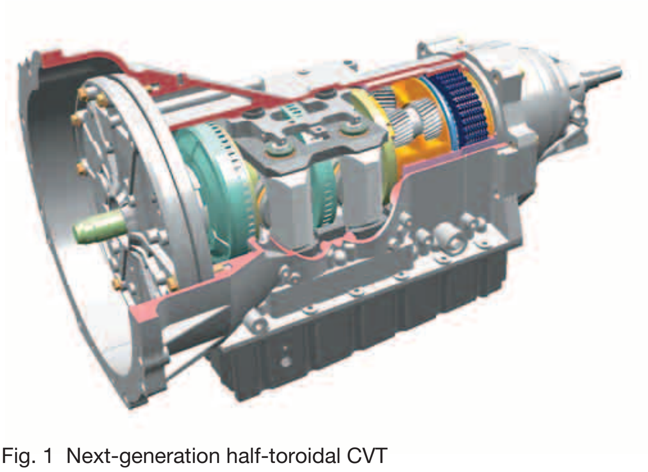

Fig. 1 Next-generation half-toroidal CVT

2.1.2 Diametrical size of transmission

Power takeoff from the variator in current half-toroidal CVTs is transmitted by the intermediate wall of the output disc's backside through a countershaft to an output shaft. This mechanism further prohibited any downscaling of the transmission's diametrical size.

2.1.3 Compatibility between downscaling and high-torque capacity design

The structure of the current CVT requires a relatively larger torque converter and variator to match the high torque of large-displacement engines. There is a trade-off between designing a transmission that can handle high-torque capacity and downscaling. A review of the current CVT structure was required to satisfy requirements of better fuel economy while also enduring the high-torque demand of large-displacement engines.

2.2 Fuel economy

2.2.1 Range of transmission reduction ratio

Current half-toroidal CVTs have a ratio range 4.33. The ratio range of the newest six-speed AT, however, is as much as 5.0 or 6.0. Although a six-speed AT has better fuel economy under high-speed operations, the wider ratio range of a half-toroidal CVT promises much better fuel economy under similar driving conditions.

2.2.2 Transmission efficiency

In current half-toroidal CVTs, clamping force plays a critical role in ensuring efficiency and long-life of the variator, which transmits all the power from the engine. Clamping force by the current loading cam method is only proportional to torque. This fact made it difficult to optimize clamping force in relation to change-speed ratios and oil temperature, which hampered improvements in torque transmission efficiency.

2.3 Ease of assembly and quality

A variator, the main component of current half-toroidal CVTs, is assembled as a subassembly of parts or components (Fig. 2). Compared to an AT, assembly of a variator is very complicated and requires stricter quality controls to ensure clean working conditions of related components during the assembly process.

3. Basic Structure

We achieved faster and simpler mounting capability by reducing the transmission size to that of a six-speed AT. We then mounted the transmission to a luxury sedan. The whole structure consisted of an oil pump, a hydraulic loader, a variator, a planetary gear, a multiplate wet clutch (for switching between low and high modes), and a hydraulic pressure control valve. Fig. 3 illustrates this configuration, and Table 1 lists the main specifications.

4. Features and Structure

The next-generation half-toroidal CVT features a geared-neutral and power-split system, and a coaxial structure for the transmission. Details are discussed here.

Fig. 2 Main parts of variator for current half-toroidal CVT

Table 1 Main specifications

Vehicle	RWD luxury sedan (1 800 kg)
Engine	4 292 cc V8 Gasoline (430 N·m/206 kW)
Torque capacity	450 N·m
Maximum input rev.	6 600 rpm
Transmission size	Compatible size and interface as 6AT
T/M Reduction ratio (T/M Speed ratio)	–6.25 to ∞ to 0.52 (–0.16 to 0 to 1.92)
Launch device	None (geared-neutral system)
T/M mass (dry)	98 kg
Oil pump type	External gear pump
Traction fluid	Idemitsu TDF 2210

4.1 Coaxial structure

Features

- Size reductions achieved by eliminating the countershaft and intermediate wall.

Structure

Since power takeoff from the variator is transmitted from the intermediate wall of the output disc backside to the countershaft, the transmission's diametrical size was large. We focused on simplifying the structure by using a coaxial layout. Size reductions were achieved by eliminating the countershaft and intermediate wall by using a coaxial structure in the power takeoff section, which uses a planetary gear mechanism as shown in Fig. 4. Diametrical size of the transmission was reduced and minimum height from the ground was increased by utilizing the newly acquired space at the bottom of the transmission where the countershaft once was. Furthermore, eliminating the intermediate wall resulted in a shorter transmission, and helped to lower costs by reducing the number of parts.

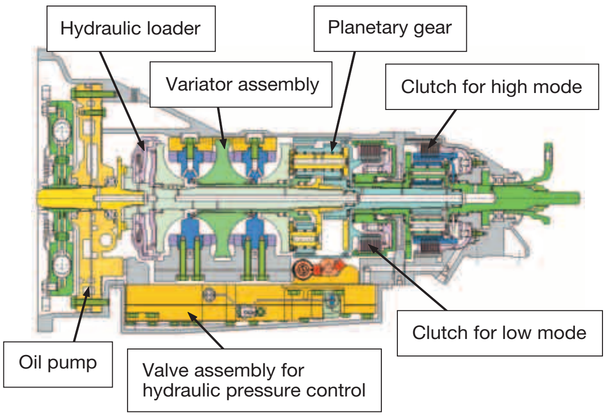

Fig. 3 Basic structure for next-generation half-toroidal CVT

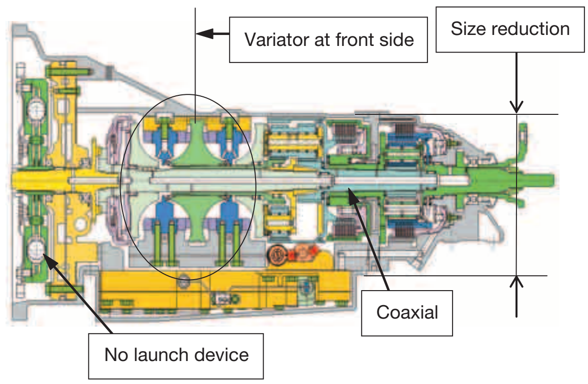

Fig. 4 Coaxial structure and geared-neutral system

4.2 Geared-neutral system

Features

(1) Size and weight reductions by eliminating the torque converter

(2) Increased maximum torque by reducing variator load

(3) Improved efficiency for launching from a standing start through the low-speed range (improved fuel economy)

(4) Powerfully smooth drive at launching from a standing start

Structure

Conventionally, a torque converter was used for a launching device. Due to its inherit characteristics, the torque converter suffered from lag-time. When the torque converter starts, only the engine rotation increases and acceleration of the vehicle is delayed, which impairs the fuel economy of the vehicle. The European market, especially, demands quick and responsive acceleration from a standing start. Additionally, the load of a variator, which is used to attain a maximum variator ratio, is increased by the torque-amplifying action of the torque converter. It was thus difficult to reduce the half-toroidal cavity diameter and, in fact, required a relatively larger half-toroidal cavity diameter to match the high torque capacity. To overcome these challenges, the next-generation half-toroidal CVT adopts a geared-neutral system that incorporates a planetary gear mechanism. This system eliminates the torque converter as the starting device, which allows reductions in size and weight of the transmission. After eliminating the torque converter, we positioned the variator towards the front (Fig. 4), which is an added benefit for automobile manufacturers. Elimination of the torque converter also reduced the load of the variator, which allows ensured compatibility between a smaller variator and increased

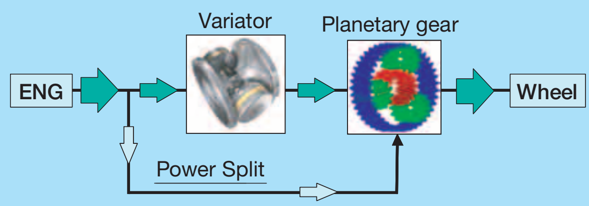

Fig. 5 Torque flow in the next-generation half-toroidal CVT

maximum torque by taking advantage of the high variator ratio when starting. This new structure offers drivers greatly enhanced performance and a powerfully smooth drive-away feeling void of any lag-time at launching from a standing start, with much better fuel economy by improving efficiency in the low-speed ranges.

4.3 Power-split mechanism

Features

(1) Ensures compatibility between the smaller size and increased maximum torque by reducing variator load

(2) Improved mid- and high-speed efficiency

Structure

The power-split mechanism is a component of the power transmission that uses planetary gears and bypasses the variator. This layout facilitates transmitting of a portion of the load directly to the planetary gears to reduce load to the variator (Fig. 5). This further makes it possible to reduce the size of the variator while maximizing torque-handling capability. Accordingly, when operating in high mode, the power-split mechanism contributes to efficiency in the mid- to high-speed range thus achieving improved fuel economy.

4.4 Two-mode structure (low and high)

Features

(1) Improves high-speed fuel economy by using a wider transmission reduction ratio range

(2) Low mode covers the low-speed range from stop to forward and stop to reverse launching

(3) High mode covers the speed range of middle to high

Structure

We adopted a planetary gear mechanism and a two-mode structure that consists of a multiplate wet clutch to take full advantage of the benefits offered in a variable speed system (Fig. 6). By adopting a two-mode structure (low and high), we were able to widen the transmission reduction ratio, and exceed the high-speed fuel economy found in the highest transmission reduction ratio of a six-speed AT (Fig. 7).

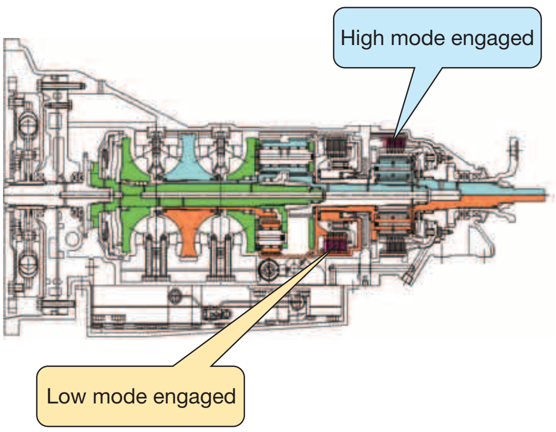

Fig. 6 High-mode and low-mode schemes

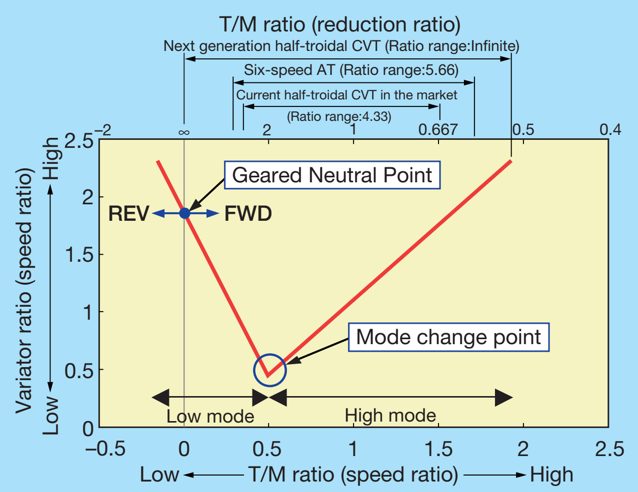

Fig. 7 Comparison of variator speed ratio for low and high modes

Comparison of transmission reduction ratio

- Current half-toroidal CVT in the market:
  2.857 to 0.660 (Coverage ratio: 4.33)
- Six-speed AT:
  3.296 to 0.582 (Coverage ratio: 5.66)
- Next-generation half-toroidal CVT:
  ∞ to 0.521 (Coverage ratio: infinite)

The low mode covers shifting for going forward and going in reverse. The low mode also serves as the starting control when combined with the geared-neutral (GN) system. This new structure offers drivers greatly enhanced performance and a powerfully smooth drive-away feeling void of any lag-time (only the engine rotation increases, but the acceleration of the vehicle is delayed) at launching from a standing start, which promises much better fuel economy by improving efficiency in low-speed ranges. When operating in high mode, the power-split (PS) system helps to reduce load on the variator, thus enabling a smaller diameter of the half-toroidal cavity.

4.5 Hydraulic loading mechanism

Features

- Improved efficiency and reduced size by optimum control of clamping force

Structure

In a half-toroidal CVT, applying clamping force to the power rollers between the input and output discs transmits torque. The current model of the half-toroidal CVT produces a clamping force by a loading cam mechanism. A loading cam mechanism is a highly reliable device that can be used to control clamping force without an external unit. However, it was difficult for the loading cam mechanism to perform optimum clamping force in relation to variator-speed ratios and oil temperature. The challenge we faced was an excessive clamping force at the low end and the high end of the variator speed ratio (see Fig. 8). By replacing the loading cam mechanism with a

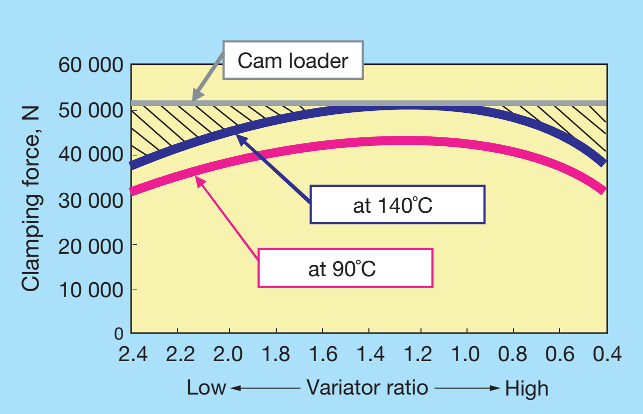

Fig. 8 Optimal clamping force by variator speed ratio and oil temperature

hydraulic loading method, optimum control of clamping force for various driving conditions is possible. Clamping force varies according to variator speed ratio, engine torque, and oil temperature. By monitoring these conditions with a control unit, fuel economy can be improved, and further size reductions of the variator can be achieved.

4.6 Modulation of variator

Features

(1) Reduced assembly costs by improving ease of transmission assembly

(2) Enhanced quality assurance at the subunit level

Structure

Presently, main components used in the variator are assembled as a subassembly (Fig. 2). Compared to an AT, assembly of a variator is very complicated and requires stricter quality controls to ensure clean working conditions of related components during the assembly process. By modularizing variator parts (Photo 1), assembly cost of the transmission can be reduced, and quality of the variator during assembly can be controlled.

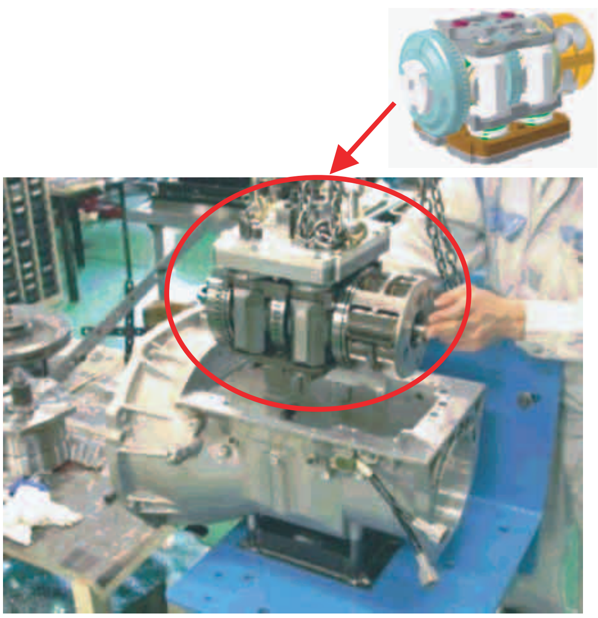

Photo 1. Modularized variator

5. Actual Field-Test Data for Verifying Effectiveness

Our newly developed next-generation half-toroidal CVT was mounted to a test vehicle. The hydraulic circuit for oil pressure control and the electronic system of the test vehicle are illustrated in Figs. 9 and 10 respectively. We tested functionality under actual vehicle driving conditions. Here, we will explain the results of verification testing and test data of each function.

5.1 Geared-neutral system control

The next-generation toroidal CVT abolishes starting devices such as the torque converter and uses a differential mechanism of variator and planetary gears, which achieves creep stop conditions, and can initiate launching with geared-neutral control. This geared-neutral control can also adjust the output shaft near the geared neutral point (for reverse, stop, and normal rotation control) while the input shaft of the transmission is rotating. An outline of the control method is as follows:

(1) Variator speed ratio control

Adjusts variator speed ratio, which can obtain optimal creep force using a step motor (open-loop control).

(2) Torque control

Calculates the optimal target torque for input to the variator by the control unit. Adjusts input torque to the variator in order to stabilize optimal target torque (creep force) using torque control valves (feedback control of oil pressure).

(3) Differential pressure control correction

Differential pressure of the trunnion detects input torque to the variator. If input torque to the variator is out of a specified range, the step motor can adjust the variator speed ratio.

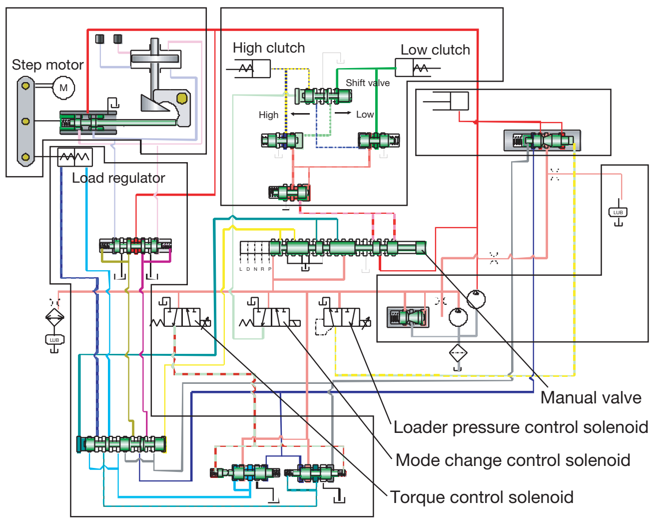

Fig. 9 Circuit diagram for oil pressure control

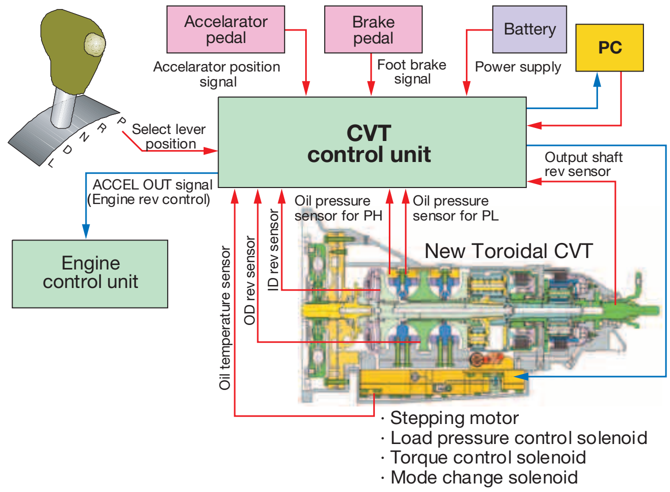

Fig. 10 Electronic system diagram

In-vehicle test results

- Shifting from Neutral to Drive, and shifting from Neutral to Reverse

Test data 1 (Fig. 11) reflects operation of the transmission from Neutral to Drive and Neutral to Reverse ranges under standstill conditions with the brakes being applied.

Creep force in the forward direction quickly occurred when connected to a low clutch in the drive range. Creep force of reverse direction quickly occurred when connected to a low clutch in the reverse range.

There were no vibrations transmitted to the geared-neutral system from the engine and stability remained high. Whereas we achieved the stability of creep force control, there was no instability of creep force. Furthermore, we confirmed that the stability of creep force was possible in the half-toroidal CVT by variator speed ratio control and differential pressure control correction without any torque control (see paragraph 5.1, 1 through 3).

5.2 Transmission ratio control

Transmission ratio control testing was conducted under vehicle acceleration from a standing stop using geared neutral control. Transmission ratio control that takes into consideration various factors such as vehicle speed, rate of depression against the accelerator pedal, and braking pressure are discussed here.

In-vehicle test results

- Start, acceleration, slowdown, and stop

Both engine speed and vehicle speed increased smoothly while pushing the accelerator, and a quick and responsive acceleration was obtained. In addition, smooth deceleration and stopping of the vehicle was achieved after applying the brake. Test data 2 (Fig. 12) illustrates conditions from a normal start to stop, and Test data 2 (Fig. 13) shows conditions from start under full acceleration to stop with strong braking.

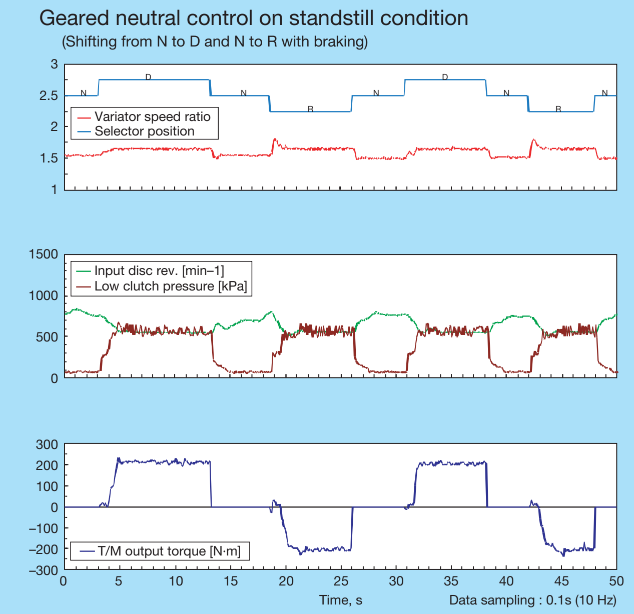

Fig. 11 Test data 1 (N→D/N→R under standstill conditions)

5.3 Mode change control

The next-generation toroidal CVT adopts either of two modes, which consist of a low multiplate wet clutch or a high multiplate wet clutch that works in combination with a planetary gear system to make the best use of continuous variable speed. Mode change occurs when the

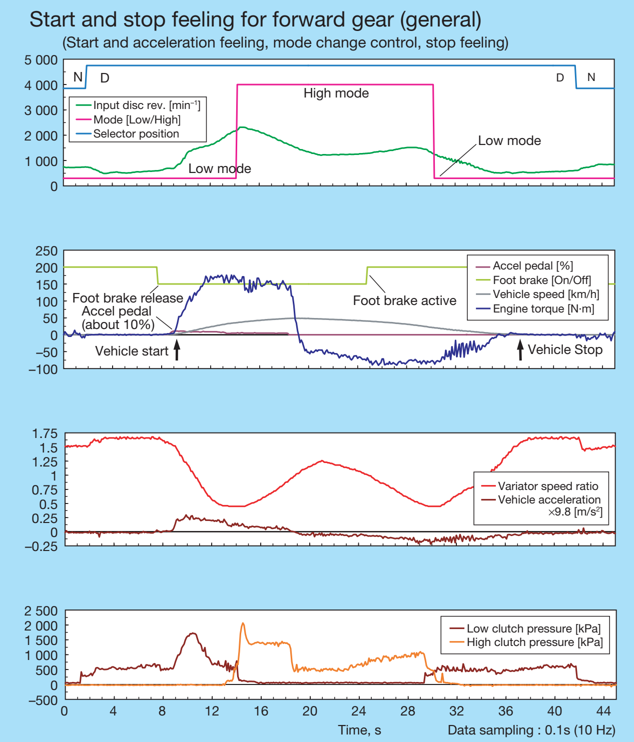

Fig. 12 Test data 2 (launching/stopping and mode changing)

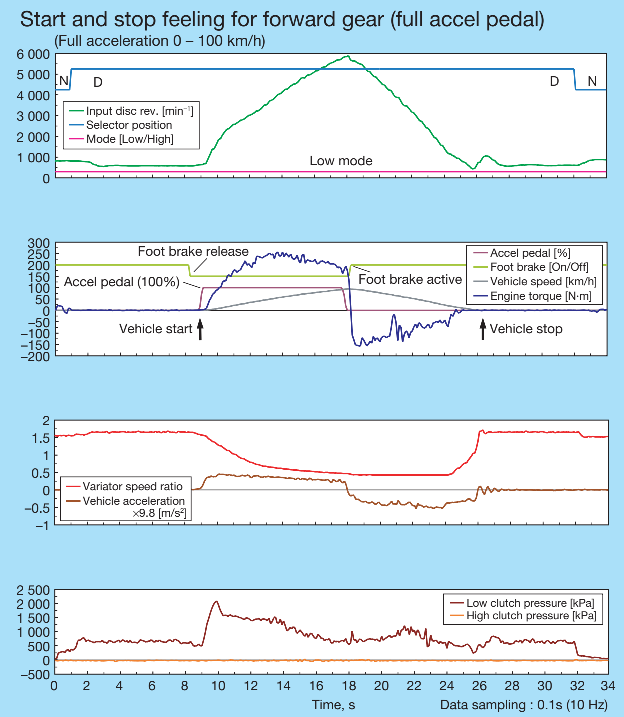

Fig. 13 Test data 3 (full accelerator launching and strong braking)

speed ratio of the variator nears the maximum deceleration (low). We were concerned about shift shock, which can occur during mode changes under abrupt acceleration. However, we were able to resolve such shift shock by engaging both low/high clutches simultaneously. Mode change data is shown below.

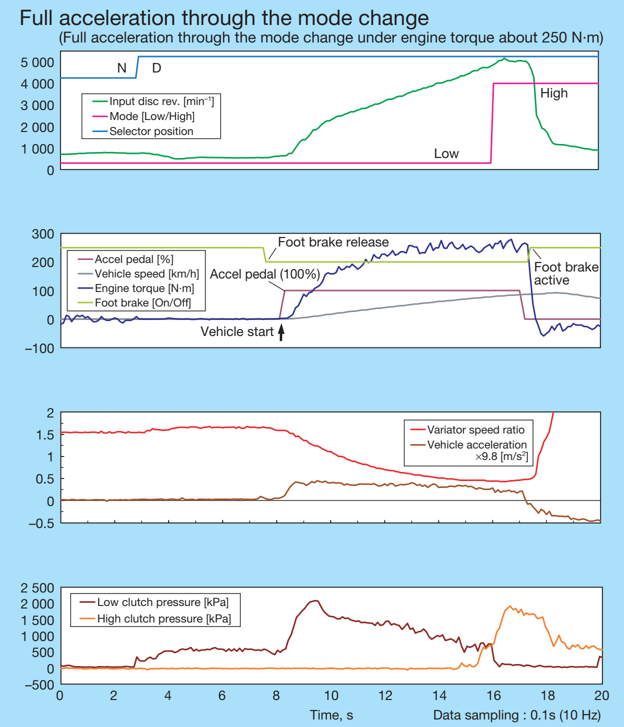

Fig. 14 Test data 4 (mode changing under full acceleration)

In-vehicle test results

While operating the test vehicle, we were unable to physically sense when changing from low mode to high mode occurred, nor when high mode to low mode changing occurred. The smoothness of mode changing was confirmed regardless of the amount of engine torque and any accelerating conditions. Furthermore, we were able to confirm quick and smooth changing under strong accelerating conditions as well. Test results of mode change control during acceleration with the accelerator pressed about 10% of the way down are shown below in Test data 2 (Fig. 12). Test results of mode change control under full acceleration are shown below in Test data 4 (Fig. 14).

6. Conclusion

We targeted various base functions of a conventional toroidal CVT for further development and demonstrated how well the new developments performed in a next-generation toroidal CVT mounted to a vehicle. We thus verified that real-world application of the next-generation toroidal CVT is highly possible.

The main points of this next-generation CVT are summarized here:

(1) Highlights of driving performance
- Powerfully smooth driving at launching from a standing start.
- Acceleration is responsive and free of any lag-time.

(2) Environmental considerations
- Expect much better fuel economy by improved efficiency, a compact size, and a wide ratio range.

(3) Developed for motor vehicles equipped with large-displacement (high-torque) engines
- Achieved compatibility between a smaller size and high torque capacity by using a geared-neutral and power-split mechanism.

The newly developed next-generation half-toroidal CVT is as compact as a six-speed AT found in luxury vehicles, which can be mated to a high-torque engine in the 450 N-m range. Improved fuel economy can be expected by focusing on enhancing efficiency, making reductions in weight and size, utilizing a coaxial structure, and by adopting a wider ratio (transmission reduction ratio -6.25 to ∞ to 0.521) in tandem with high and low modes. Additional features include quick and smooth launching

Table 2 Variator dimension

Cavity diameter D	124 mm
Input disc diameter	148 mm
Output disc diameter	158 mm
Disc radius Ro	37.5 mm
Contact angle θ	62.5°
Number of Power Rollers	4

from a standing start, which was achieved by eliminating the torque converter. Variator specifications are shown in Table 2. Although we were faced with challenges regarding the geared-neutral start control without a torque converter, we succeeded in optimizing change control in the low and high modes, which allowed us to mount the CVT to vehicle with a high-torque engine in the 450 N-m range for demonstrating real-world use and functionality. Taking advantage of proprietary control technologies, we will further our efforts with a special focus on durability and reliability of the total system, and develop fail-safe characteristics necessary for mass-produced motor vehicle applications.

7. Postscript

We have successfully developed a next-generation half-toroidal CVT that is compact, highly efficient, and can be mated to a high-torque engine. This achievement meets the demands of a new era amid stronger calls for reducing the impact of automobiles on the environment. In-vehicle field-testing revealed new issues that could not be found in theoretical calculations. Accordingly, improvements were made and new field-testing was conducted. Our results conclusively show our next-generation half-toroidal CVT is ready for real-world applications.

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High-Performance Standard Roller Bearings—HPS™ Spherical Roller Bearings

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ABSTRACT

Spherical roller bearings are used extensively in various equipment and machinery .The high-load capacity and self-aligning capability of spherical roller bearings, in addition to their easy-to-handle non-separable design, make them highly favored among users as general-purpose roller bearings. Consequently, such applications impose rigorous standards of long service life and high reliability on the bearings they use. Introduced to the market in 2004, NSK's High-Performance Standard (HPS) series of spherical roller bearings are high-performance products that provide various industries with long service life and high-speed rotation capability to meet the needs and requirements of equipment and machinery used in their operations. In this paper, the features of the HPS series of spherical roller bearings are introduced.

1. Introduction

The main features of spherical roller bearings are high-load capacity, self-aligning capability, and an easy-to-handle non-separable design. These features help ensure outstanding performance across a wide range of applications found in iron and steel works, paper mills, mining machinery, construction machinery, transportation equipment, and wood working machinery. In addition to the above features, spherical roller bearings must provide long life and high reliability.

In 1998, NSK commercialized the EA series[1)] of high-performance spherical roller bearings in response to such expectations and needs. It was well received by users in Japan and overseas. The EA series incorporated the following features, which were improvements on NSK's earlier product, the CD series:

- Increased load capacity (increased number of larger roller elements)
- Higher limiting speeds and lower heat generation (cage flange for guiding rollers)
- Higher cage strength (double-flanged cage)

In recent years, demands for longer life and higher limiting speeds have increased. This led to the development of NSK's high-performance standard (HPS) series of spherical roller bearings (Photo 1) in 2004.

The result was a newly developed high-performance standard bearing, or HPS for short. NSK's HPS spherical roller bearings are the result of fusing advanced life analysis and processing technologies. The result is a bearing that offers users longer service life at higher limiting speeds. Compared to the EA series, HPS spherical roller bearings are much more versatile in that they meet the needs of a broader range of applications.

Photo 1 HPS™ spherical roller bearing

2. Long-Life Ensured by Preventing Generation of Microstructural Fatigue Cracks

Spherical roller bearings typically have two rows of barrel-shaped rollers positioned between one spherical outer ring raceway and two inner ring raceways, which provide a self-aligning capability.

Due to the spherical configuration of these bearings, slippage within the bearing occurs at the contact points between the rollers and the inner and outer ring raceways under true rolling motion of the rollers. Under normal rolling conditions, however, the rollers are unable to maintain true rolling motion and suffer from differential slip and spin slip. NSK was able to clarify the mechanism that allows spherical roller bearings to produce friction force (and tangential force), which greatly influence bearing fatigue life. Details regarding this mechanism will be discussed in the next issue of Motion & Control.

The ratio of actual life to calculated life of spherical roller bearings is shorter than that of other types of bearings even under ideal conditions including sufficient oil film formation and clean lubricating oil (Fig. 1).

Figure 2 illustrates the fatigue pattern for ball bearings where a peak in the fatigue index indicates that fatigue initiated internally rather than externally.

Conversely, Fig. 3 illustrates the fatigue pattern index for spherical roller bearings where a peak in the fatigue index indicates that fatigue started externally. Figure 3 also shows that the fatigue level was highest at the surface of the bearing, which further diminished bearing life. This, we believe, is the primary mechanism that is responsible shorter bearing life.

Surface fatigue of spherical roller bearings typically occurs along the circumferential zone near the center of the inner ring raceway. Microstructural changes in this zone evolve into cracks that propagate and lead to flaking.

During the development of the HPS series, we focused our research on the friction force (and tangential force), and studied how they relate to the generation of microstructural cracks that ultimately lead to shortened fatigue life. We were then able to reduce rolling friction, which helped to reduce the generation of microstructural cracks. To reduce roller slippage, we employed a special surface treatment to the outer ring raceway surface. Photo 2 shows the surface of the inner ring raceway of a newly developed product after testing was conducted under the same conditions as Fig. 4. The microstructural crack, which was observed on the conventional spherical roller bearing, did not appear on the developed product. This shows that the special surface treatment is an effective measure against the generation of microstructural cracks.

Fig. 5 shows results of life evaluation tests for three types of conditions. The vertical axes represent life ratios where the conventional EA series of spherical roller bearings show a ratio of only 1 and the HPS series show much longer life ratios for all three test conditions.

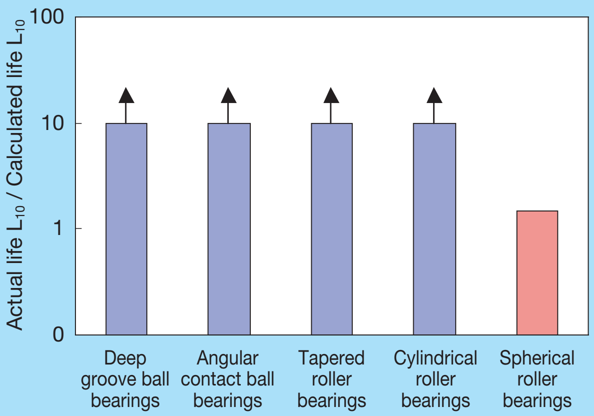


Fig. 1 Relationship between ratio of actual life and calculated life for various bearings

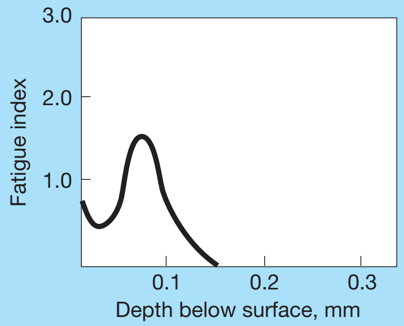


Fig. 2 Fatigue pattern of ball bearings

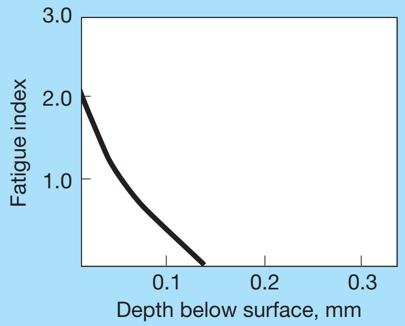


Fig. 3 Fatigue pattern of spherical roller bearings

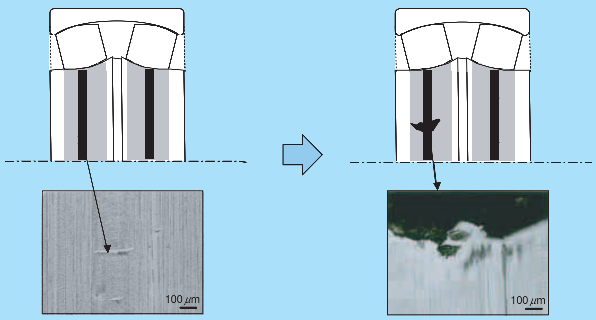


Fig. 4 Failure mechanism of spherical roller bearing

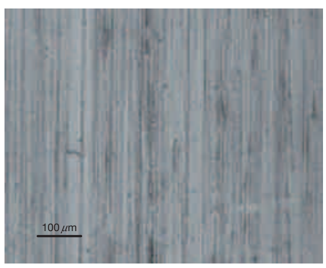


Photo 2 Appearance of inner ring raceway of newly developed product after testing

3. Higher Limiting Speed Achieved by Improving Cage Design

The cage design in a spherical roller bearing greatly influences bearing performance. In additions to the raceways and rollers, the cage must be highly functional and highly accurate.

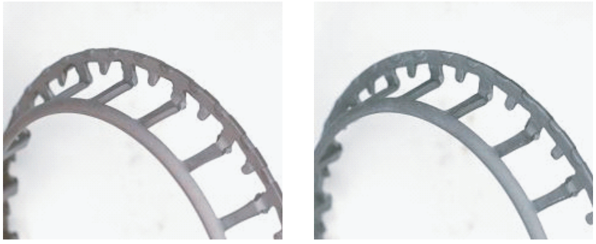
Conventionally, pressed steel cages were treated with a phosphoric acid-manganese coating. However, wear resistance suffered due to the fragile nature of the coating. As the operating environment of spherical roller bearings became increasingly harsh over the past several years, concerns over cage wear became ever more critical.

The HPS series addresses these concerns with a wear-resistant nitride-treated cage. NSK uses a special nitriding treatment that consists of an inner layer and an outer layer. The inner layer, which is a dense compound layer that is predominately iron nitride, provides greater hardness than the conventional nitriding. The outer layer enhances seizure and wear resistance. This special nitriding treatment achieves new performance levels that have never been realized before with conventional nitriding treatments.

An additional benefit is that the special nitriding treatment is performed at lower temperatures, which helps to minimize any deformation due to heat and helps to maintain diameter accuracy throughout the coating process.

Photo 3 shows both the conventional cage and the newly developed cage. Figs. 6 and 7 list evaluation test results, and Fig. 8 provides drop impact test results.

According to the results illustrated in Fig. 6, we can see that the level of wear resistance of the HPS spherical roller bearings is much higher than that of the conventional EA series. Fig. 7 further illustrates that even after extensive testing, cage wear in the HPS bearings progressed at a significantly slower rate than that of the EA product. Moreover, the cage of the HPS series ensures enhanced strength as illustrated in Fig. 8. The results of these tests confirm that the maximum limiting speed of the HPS spherical roller bearing is 20% higher than that of conventional EA spherical roller bearings.



Special nitride-treated cage   Phosphoric acid-manganese treated cage

Photo 3 Newly developed special nitride-treated cage and the conventional phosphoric acid-manganese treated cage

4. Other Features

HPS spherical roller bearings provide dimensional stability under high-temperature operating conditions up to 200°C. The special nitride-treatment given to the high-accuracy steel cage, which was adopted in the EA series, works to maintain the conventional features of low vibration and low noise.

Test conditions

Test bearing: 22211 (Bore diameter 55 mm × Outside diameter 100 mm × Width 25 mm)
Load: ①Radial load: Fr=45.22kN (Fa/Fr=0)
Axial load: Fa=0 kN
②Radial load: Fr=26.31 kN
Axial load: Fa=6.58 kN (Fa/Fr=0.25)
Lubrication: Forced oil circulation
Lubricant: Mobil oil (ISO VG68)

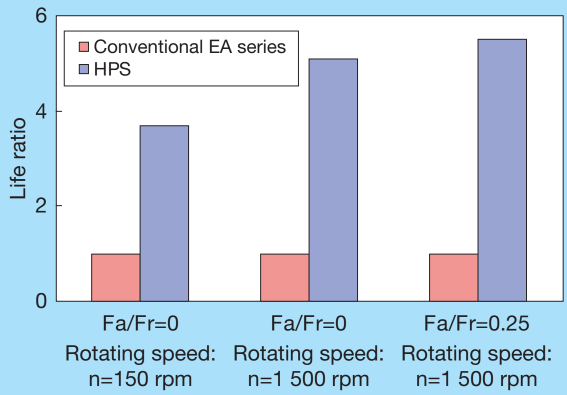


Fig. 5 Results of life evaluation tests

Test conditions

Test bearing: 22211 (Bore diameter 55 mm × Outside diameter 100 mm × Width 25 mm)
Load: Radial load: Fr=15.47 kN
Lubrication: Grease lubrication
Lubricant: NS HI-LUB grease

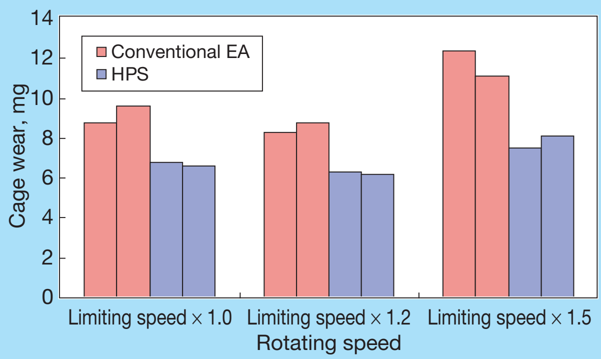


Fig. 6 Cage wear evaluation results

Test conditions
Test bearing: 22310 (Bore diameter of inner ring 50 mm × Outside diameter of outer ring 110 mm × Width 40 mm)
Load: Radial load: Fr=11.05 kN; Acceleration of vibration: 35 m/s^2
Rotating speed: 3 100 rpm
Lubrication: Oil bath lubrication
Lubricant: Tellus Oil (Shell) C (ISO VG5)

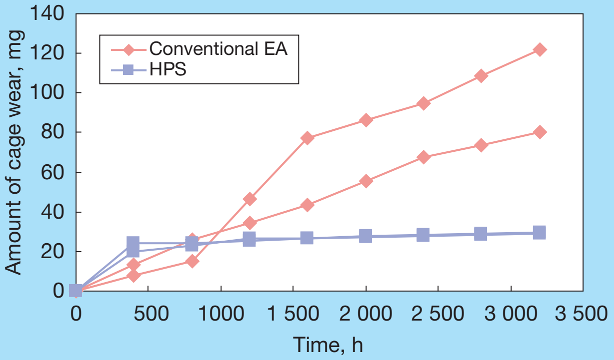


Fig. 7 Cage durability evaluation results

Test conditions
Test bearing: 22210 (Bore diameter of inner ring 50 mm × Outside diameter of outer ring 90 mm × Width 23 mm)
Acceleration impact: 1 960 m/s^2

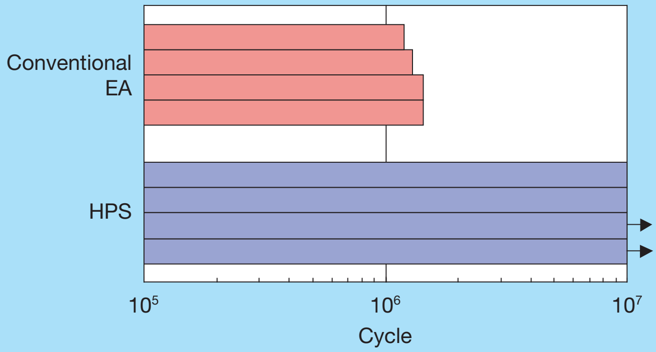


Fig. 8 Drop impact test results

5. Conclusion

The newly developed HPS spherical roller bearing is available in 42 bearing numbers of three dimension series (222xx, 213xx, 223xx) with an inner bore diameter ranging from 40 mm to 130 mm.

The HPS series bearings offer users dramatically improved performance in comparison to the EA series, and are suitable for a variety of applications used in iron and steel works, paper mills, mining machinery, construction machinery, and others. We believe this product will be increasingly chosen for use in diverse fields both in Japan and overseas.

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Pulley Support Bearings for Push-Belt CVTs

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ABSTRACT

Pulley support bearings of the input and output shafts in a speed change system of a push-belt CVT (belt CVT) occasionally suffer from premature flaking, which is often accompanied by the generation of white structures or microscopic cracks. NSK has proven that premature flaking with white structures or microscopic cracks is caused by hydrogen penetrating into bearing steel. Based on this mechanism, NSK has developed BELTOP bearings for belt CVTs. Until now, UR bearings and Hi-TF bearings have been used in belt CVTs for longer life. BELTOP bearings are now available in a complete lineup of series that are being promoted as the optimal bearing specification for belt CVT applications.

1. Introduction

Automobile transmissions play an important role in transmitting optimum driving force to the wheels under varying driving conditions. Transmissions are typically classified as either manual transmissions (MTs) or automatic transmissions (ATs). To shift gears in a manual transmission, the driver selects the appropriate gear by operating a shift lever while pressing on the clutch pedal. Automatic transmissions eliminate this series of operations for shifting gears. Automatic transmissions, in turn, can be further classified into automatic gear-shift transmissions and continuously variable transmissions (CVTs).

In recent years, CVTs on the market have adopted Van Doorne-designed multi-segment metal belts for use in some front-wheel-drive passenger cars.

This paper presents the features of pulley support bearings for push-belt CVTs (belt CVTs), as well as NSK's long-life technology.

2. Features of Belt CVTs

2.1 Variable speed mechanism

CVTs inherently ensure smoother upshifting and downshifting characteristics, free of shift shock associated with conventional gear-change units. CVTs also enhance fuel economy since they allow the engine to always run at optimum speed for any given speed ratio. The mechanism by which belt CVTs change speed is described below.

A belt CVT (Fig. 1) consists of three basic parts: a primary pulley pair (driving sheave) on the crankshaft (input) side, a secondary pulley pair (driven sheave) on the driven shaft (output) side, and a multi-segment metal belt (or V-belt) that transmits torque between the pulleys. Each pulley pair consists of a stationary cone pulley and an adjustable cone pulley. The belt rides along V-grooves in the pulley pairs. When the adjustable cone pulley moves in the axial direction, the belt rides higher or lower in the groove and the belt pitch radius decreases or increases. The ratio of the pitch radius on the driving sheave to the pitch radius on the driven sheave determines the speed ratio (a ratio of engine shaft speed to driven shaft speed). Speed ratio is represented as a ratio of the belt pitch radius on the driving sheave to the pitch radius on the driven sheave (Equation 1).

$$\text{Speed ratio} = \frac{\text{Input side pulley pair rotation speed}}{\text{Output side pulley pair rotation speed}}$$

$$= \frac{\text{Output side belt pitch radius}}{\text{Input side belt pitch radius}} \cdots\cdots\cdots\cdots (1)$$

Besides continuously changing the speed ratio using pulleys and a belt, CVTs also feature infinite ratios and a broader ratio spread. Speed ratio varies depending on individual belt CVT units; however, it typically falls in a range of 0.4 (high-speed ratio) to 2.4 (low-speed ratio). The maximum rotation speed of the output side pulley pair at a high-speed ratio is approximately 12 000 rpm.

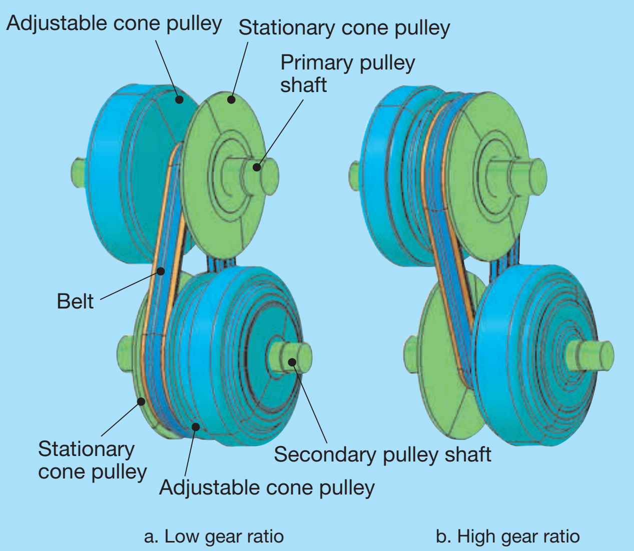


Fig. 1 Position of pulleys and belt during low-and high-speed changes

2.2 Torque-transmitting mechanism

The belt is configured of approximately 250 to 430 metal plates (elements) clamped together with two laminated bands running on both sides of the elements (Fig. 2). Each laminated band consists of about ten 0.2 mm thick metal sheets welded together that are then laminated together to form a single band. The band works to prevent excess bending stress when the belt is wound around a pulley.

Frictional force between the elements and the pulleys is what transmits the torque. The frictional force varies according to the friction coefficient between each element and a pulley, and the pressing force of the pulley against the element. Since the friction coefficient between each element and pulley under oil lubrication is about 0.08 to 0.10,[1] the pulley must exert a large pressing force (generally controlled by a hydraulic system) to prevent each element of the belt from slipping on a pulley. However, if the pulley exerts too much force, rotational friction of the belt may increase, or load on the belt, the pulley, or the pulley support bearings may increase, possibly resulting in damage to the belt or pulley.

2.3 Role of lubricating oil

Oil used in belt CVT applications provides the following functions:

(1) Facilitates activation of the movable pulley
(2) Provides lubrication between the contact surfaces of the belt elements and pulleys
(3) Provides lubrication between the belt elements
(4) Facilitates the transmission of torque in the torque converter
(5) Facilitates activation of the lockup clutch, the forward/reverse change clutch, the brake, as well as lubrication of the sliding surfaces
(6) Provides lubrication of the gears and bearings

Two types of lubricating oil are available: automatic transmission fluid (ATF), which is used commonly with automatic transmissions, and CVT fluid, which is specifically for belt CVTs. Both ATF and CVT fluid exhibit a relatively low dynamic viscosity of approximately 30 mm^2/s (at 40°C) in order to reduce loss due to agitation resistance of the oil. An additive[2] is used with CVT fluid to maintain a balance between the high friction coefficient and abrasion prevention performance.

A high-pressure pump delivers lubricant to various components, and circulates lubricant throughout the CVT unit. In the event of significant leakage from the pump or from a sealing ring in the lubricant line, various components may suffer from lubricant-starved conditions.

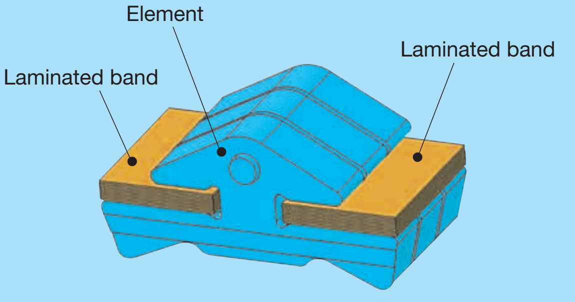


Fig. 2 Cross-section view of metal belt construction

3. Features of Pulley Support Bearings

3.1 Bearing types

Each pulley shaft is supported by two bearings as shown in Fig. 3. NSK's designation of each location is provided below.

① Primary-front bearings (Pri/Fr)
② Primary-rear bearings (Pri/Rr)
③ Secondary-front bearings (Sec/Fr)
④ Secondary-rear bearings (Sec/Rr)

Typical bearings used in each location are shown in Table 1. Two types of bearings are used: deep groove ball bearings and cylindrical roller needle bearings.

3.2 Internal design

Generally, belt misalignment (Fig. 4) directly affects belt life. One of the factors in misalignment is displacement of the pulley support bearings. To reduce this displacement, the pulley support bearings must be minimized to prevent displacement through minimal bearing internal clearance, and must ensure maximum rigidity. Initial clearances of NSK pulley support bearings are designed to be as small as possible insofar as they provide satisfactory belt life and are controlled within a smaller range than standard bearings. To minimize elastic displacement from external loads, each section of various types of belt CVTs incorporates optimum internal design.

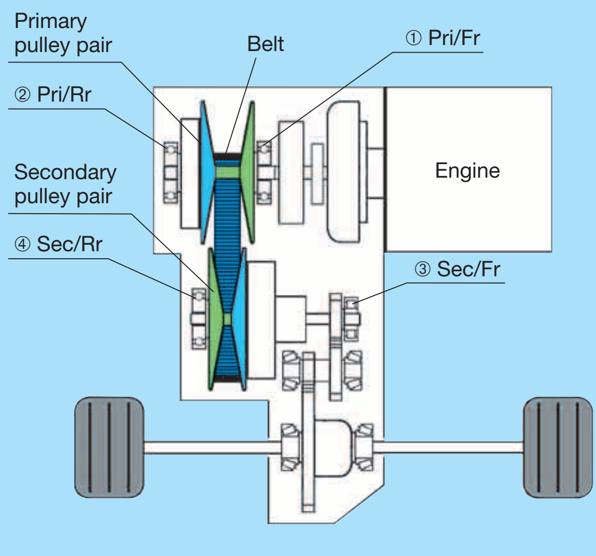


Fig. 3 Location of the pulley support bearings

Table 1 Types of pulley support bearings

		Front side	Rear side
Primary pulley	Combination 1	① Deep groove ball bearing	② Deep groove ball bearing
	Combination 2	① Cylindrical roller bearing (needle bearing)	② Deep groove ball bearing
Secondary pulley shaft	Combination 1	③ Deep groove ball bearing	④ Deep groove ball bearing
	Combination 2	③ Cylindrical roller bearing (needle bearing)	④ Deep groove ball bearing

3.3 Material and heat treatment

Belt CVTs use NSK's long-life material and heat-treatment technology, which have proven to be suitable for manual and automatic transmissions.

(1) UR treatment: carbonitriding is applied to SUJ2 (equivalent to SAE 52100) bearing steel.

(2) Hi-TF: carbonitriding is applied to NSK's proprietary TF steel.

Both treatments counter premature flaking that occurs where bearings are exposed to foreign matter, such as wear particles, in the lubricating oil.

4. Premature Flaking Specific to Pulley Support Bearings

4.1 Factors and characteristics of flaking

Some premature flaking that is occasionally generated in pulley support bearings appears to differ from subsurface originated flaking due to normal rolling fatigue, or surface originated flaking that originates from an indentation resulting from the entry of contamination.

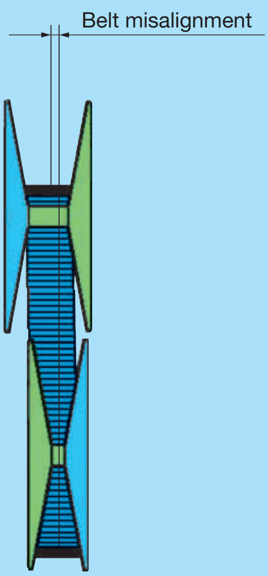


Fig. 4 Example of belt misalignment

Fig. 5 illustrates a case where flaking originated not from stress concentrations associated with the indentation process, but originated from a number of cracks that extended in the axial direction. Additionally, crack depth ranged from 100 to 200 μm beneath the surface of a cross section of the affected area, and extended in the direction of rolling element motion, which was nearly parallel to the raceway surface.

Fig. 6 illustrates a case where white microstructures and microscopic cracks appeared in the microstructure of the bearing steel material, which was taken from a cross section of the affected area.

Various theories have been advanced regarding the mechanism that generates white microstructures, as found in the cross section of the affected flaked area, including the bending stress and vibration theory,[3] and the plastic strain localization theory.[4] Recent research has shown that hydrogen-induce white structures can be reproduced,[5] which proves that in some cases, white microstructures cannot be explained using only bending stress or plastic strain localization theories.

Based on flaking that accompanied white microstructural changes in a bearing material test piece, research has proven that the generation of white microstructures, which follows hydrogen penetration, cannot be determined solely by the absolute amount of penetrated hydrogen since the rate of hydrogen penetration is very high under conditions where white microstructures are generated.[6] Based on these results, flaking accompanying white microstructural changes can be identified as hydrogen-induced flaking, mainly due to the significant influence of hydrogen (see the article, "Long-Life Materials Countering White Microstructure Flaking," in this issue of Motion & Control).

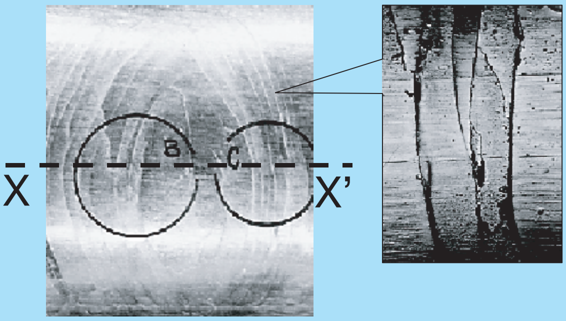
4.2 Causes of hydrogen generation and penetration into bearing steel

The generation and penetration of hydrogen into bearing steel and the consequent appearance of premature flaking are believed to occur as follows:

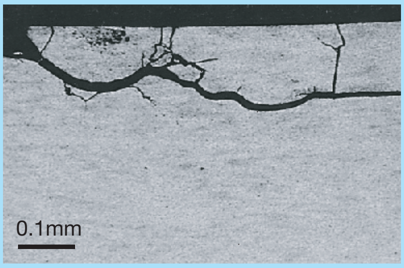
- Hydrogen is generated by decomposing lubricant when rolling elements slide on raceway rings.
- The hydrogen then penetrates the bearing material from the surface of rolling elements and raceway, activated by the contact of the metal components.

Based on this understanding, the correlation between sliding and the generation of white microstructures was examined.

Various types of sliding can occur between rolling elements and raceway rings, including differential slip, rotational sliding, revolution sliding, spin slip, and gyroscopic slip. This paper describes the evaluation results associated with differential slip. A life test (Fig. 7) was carried out using 6202 deep groove ball bearings under oil bath lubricating conditions that changes the raceway groove radius of the outer and inner rings. Specially



(a) Appearance of flaking



(b) Microstructure in cross-section X-X'

Fig. 5 Premature flaking of a pulley support bearing (Case 1)

blended synthetic oil, which included various additives, was used as the lubricant. The oil had nearly the same dynamic viscosity (30.4 mm²/s at 40˚C) as that of commercial CVT fluid.

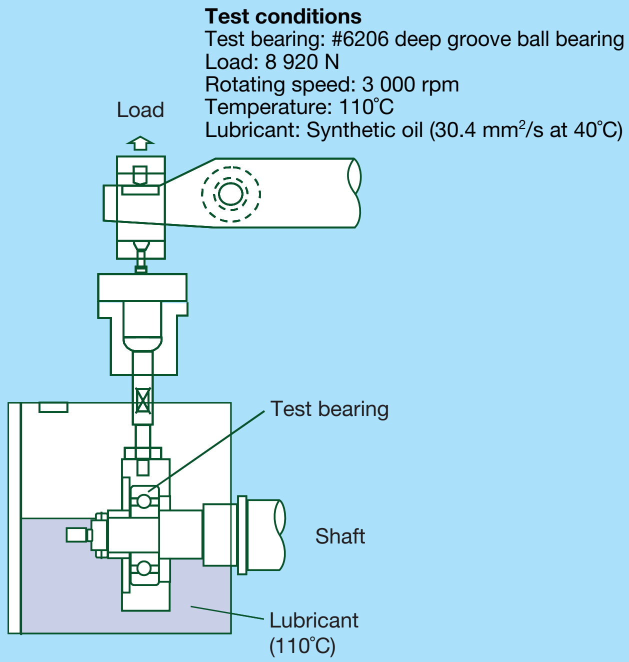


Fig. 7 Cross-section view of life test machine

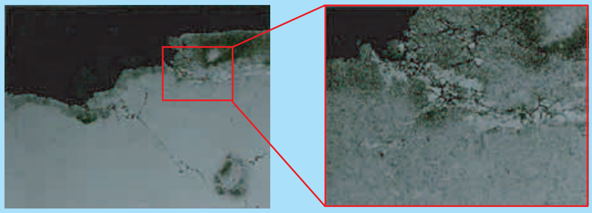


Fig. 6 Premature flaking of a pulley support bearing (Case 2)

In general, a smaller raceway groove radius (ratio of raceway groove radius to ball diameter) yields a longer calculated bearing life because the maximum contact pressure becomes small. However, the life test results shown in Fig. 8 show that a smaller raceway groove radius (ratio of raceway groove radius to ball diameter) tends to result in shorter life.

Fig. 9 shows flaking on the raceway surface, and shows a cross-section of microstructures beneath the raceway surface, which were observed on a bearing with the largest raceway groove radius. This bearing failed at approximately one-third of the calculated life. Flaking was not generated at the raceway bottom center, but instead, near the raceway shoulder. The axial cross-section of the microstructures shows some white microstructures in the area that runs symmetrically on both sides of the raceway center and slightly towards the raceway shoulder.

Fig. 10 shows the analysis results of the PV value (P: contact surface pressure; V: sliding velocity; PV: product of contact surface pressure and sliding velocity) obtained under test conditions using the bearing mentioned above (52.5/50.5). The PV value appears large in the area symmetrically on both sides of the raceway center and toward the raceway shoulder. The area where white microstructures were generated (Fig. 9) coincides with the area where the PV value is large; therefore, the

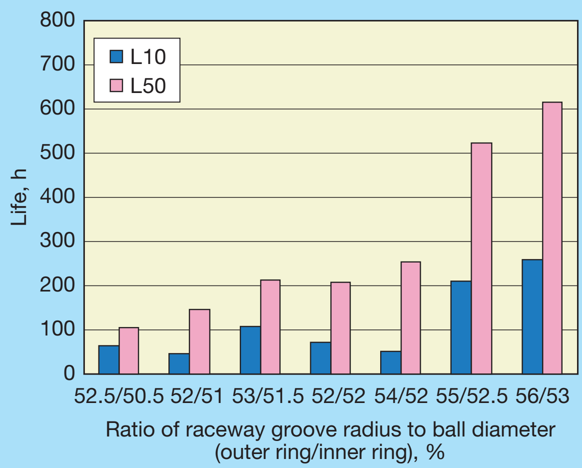
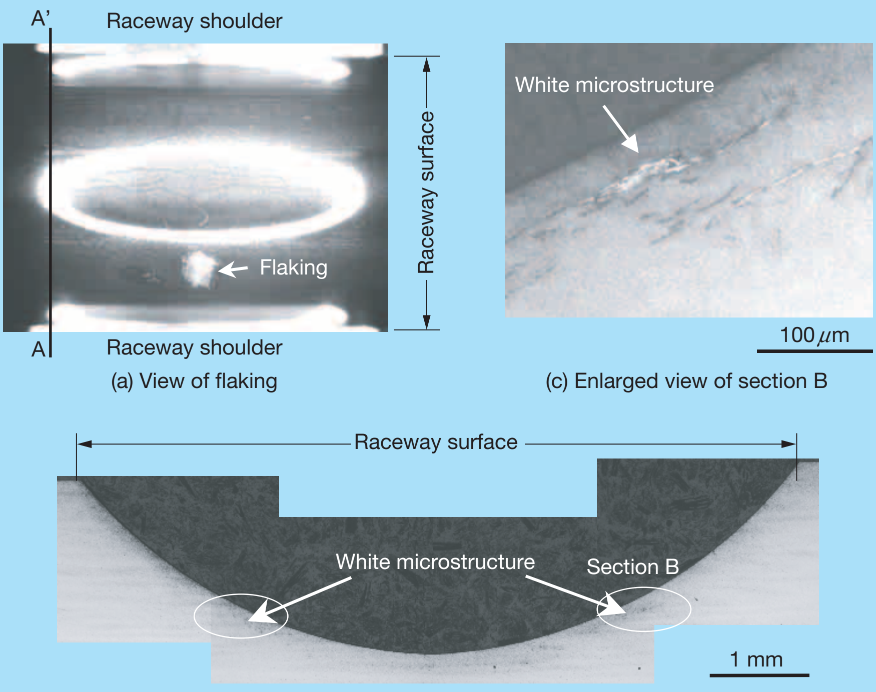


Fig. 8 Bearing life test results showing the influence of raceway groove radius



(a) View of flaking

(c) Enlarged view of section B

(b) Microstructure in cross-section A-A'

Fig. 9 Example of flaking and cross-section views of tested bearing's internal structure

generation of white microstructures (generation and penetration of hydrogen) has a strong correlation with sliding.

Next, the effect of oil additives was examined. Fig. 11 shows results of the life test that was performed under the same test conditions, using additive-free oil after removing additives from the synthetic oil described above. While the bearing life was shortened to about one-third that of the calculated life under oil lubrication containing additives, the bearing that was lubricated with additive-free lubricant did not fail—even after testing that was equivalent to three times the calculated life. Based on these results, it can be concluded that some oil additives have a strong correlation with the formation of white microstructures through the generation and penetration of hydrogen.

Fig. 12 illustrates the mechanism of premature flaking in pulley support bearings. Although actual operating

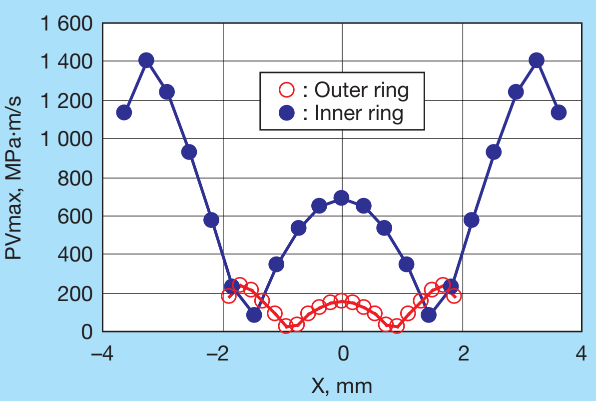


Fig. 10 Pressure and velocity (PV) value analysis results

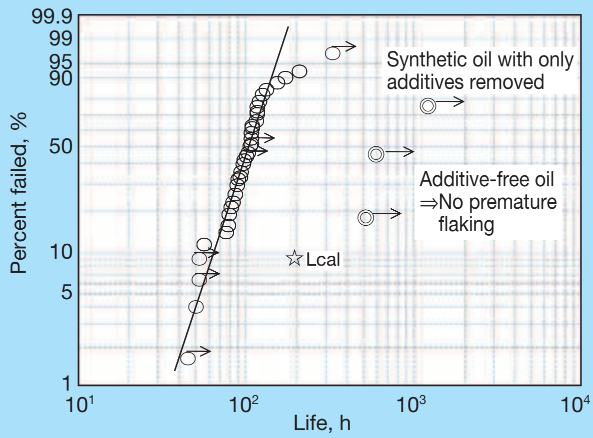


Fig. 11 Life test results showing the influence of additives in synthetic oil

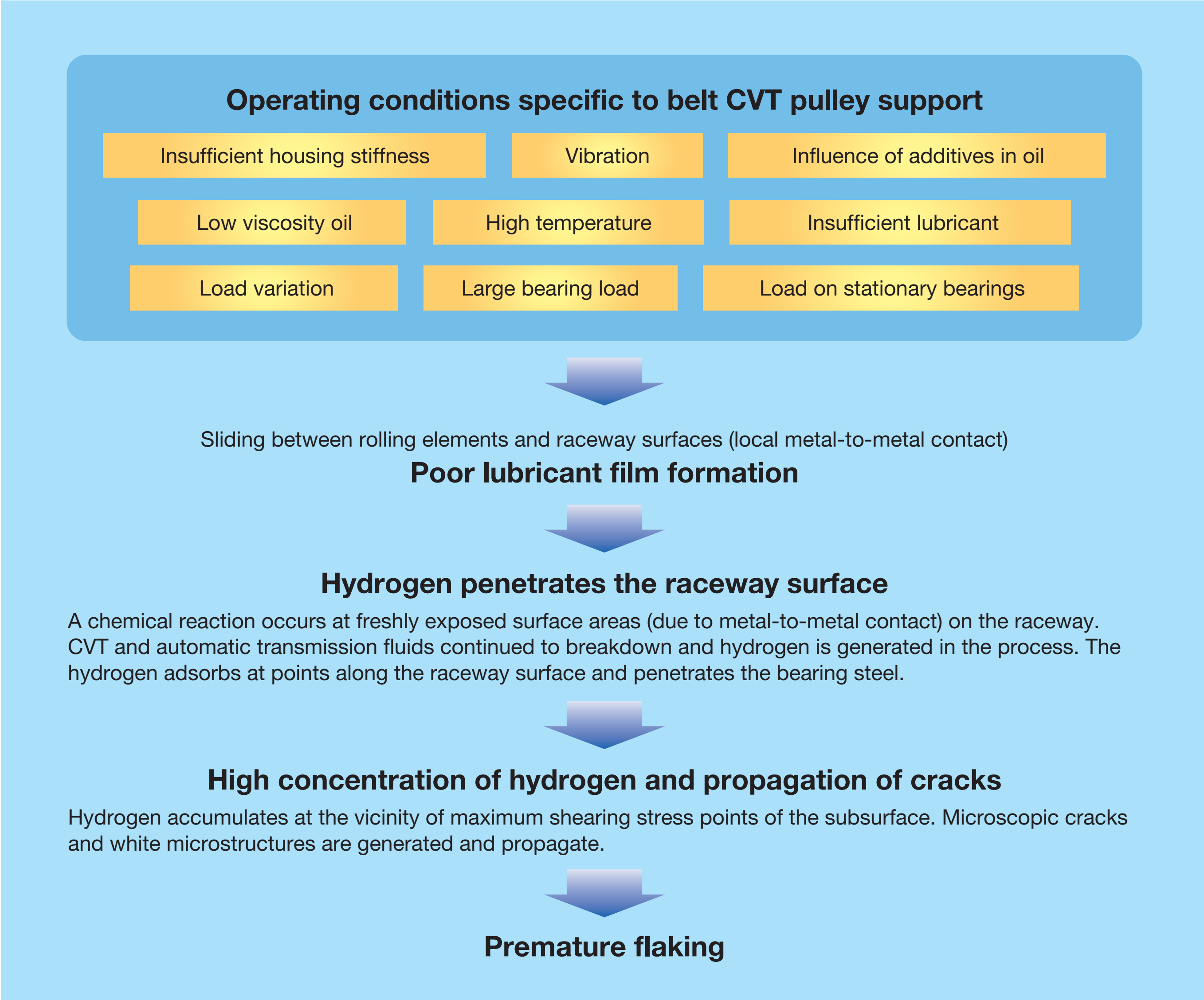


Fig. 12 Process of premature flaking in pulley support bearings of a belt CVT

conditions of pulley support bearings for belt CVTs vary from unit to unit, hydrogen induced flaking is generated by many of the listed conditions.

5. Long-Life Technology for Pulley Support Bearings

NSK has developed the BELTOP bearing—a long-life pulley support bearing that is effective in preventing the penetration and concentration of hydrogen in bearing steel. BELTOP bearings adopt newly developed SHX3 case-hardened steel, which contains an increased amount of chromium that has the effect of preventing the penetration and diffusion of hydrogen in bearing steel. The same heat treatment applied to TF technology products, such as Hi-TF bearings, is also used for the BELTOP bearings. It has been proven that BELTOP bearings exhibit an operating life that is more than ten times longer than SUJ2 bearing steel for hydrogen-induced premature flaking conditions and about fives times the life for surface-originated flaking under contaminated lubrication conditions (see the article, "Long-Life Bearings for Belt CVTs—BELTOP Bearings," in this issue of Motion & Control).

Fig. 13 summarizes the historical development of NSK's long-life rolling bearing technology. The UR bearings and Hi-TF bearings shown in the figure have also been extensively used for belt CVTs. The manufacturing process of UR bearings allows the compressive residual stress in the surface layer to function effectively for preventing cracks from generating and propagating. The manufacturing process of Hi-TF bearings utilizes a fine carbonitriding process that allows the compressive residual stress in the surface layer to prevent penetration and diffusion of hydrogen into the subsurface layer.

By including BELTOP bearings with other UR bearing and Hi-TF bearing products, we can now offer customers a

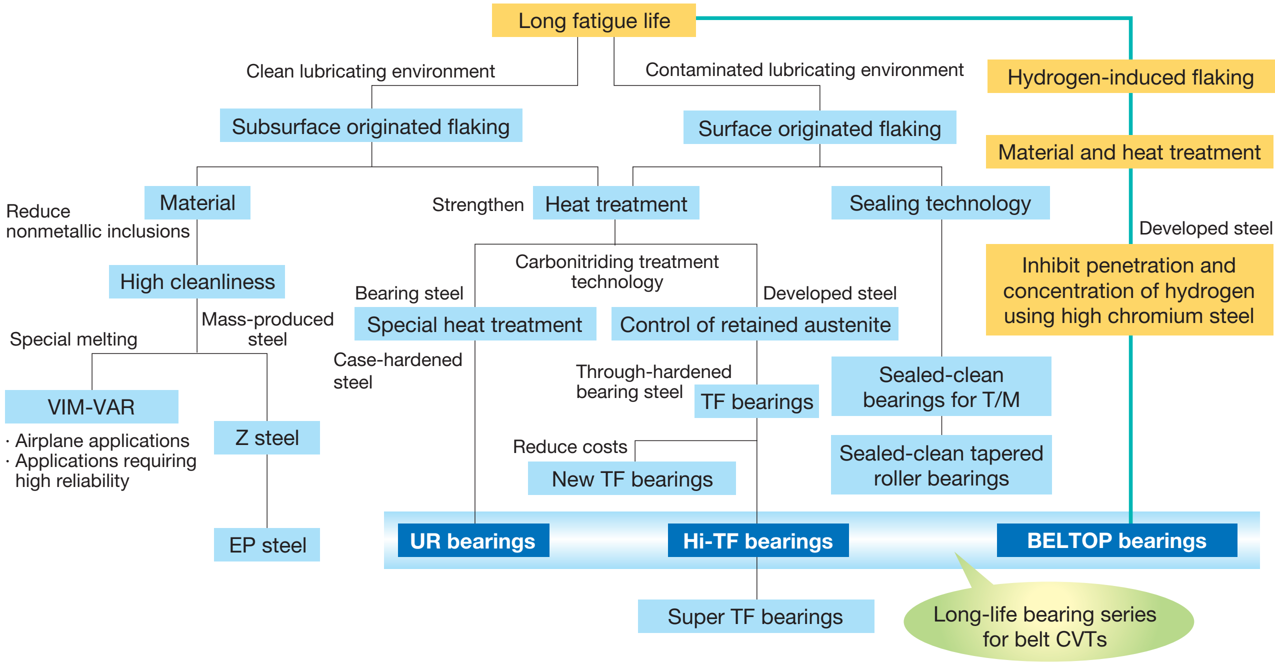


Fig. 13 Diagram showing historical development of NSK's long-life technology

complete lineup of long-life bearings for belt CVTs, which advances our ability to offer optimum bearing specifications for various types of belt CVTs.

6. Postscript

Belt CVTs were initially developed as the ideal speed reduction mechanism. CVTs are free of shift shock, and continue to attract attention for their efficiency, which enhances fuel economy, and for their integrated control with the engine. We expect that NSK's long-life bearing series for belt CVTs will contribute to protecting the environment.

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Long-Life Materials Countering White Structure Flaking

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ABSTRACT

Bearings used in push-belt Continuous Variable Transmissions (b-CVT) and engine-driven accessories may occasionally generate a white microstructure in the bearing material directly beneath the origin of flaking (referred to as "white structure flaking" by NSK), which can result in premature failure of the bearings. NSK research has identified the mechanism of so-called white structure flaking as a process where hydrogen penetrates into the bearing steel, causing it to weaken. Based on this flaking mechanism, NSK developed long-life materials to counter white structure flaking: SHX3 material (surface-hardened steel) and SHJ5 material (through-hardened steel).

1. Introduction

NSK established a long-life bearing technology by analyzing the mechanism of rolling contact fatigue in order to develop long-life bearings (Fig. 1). This technology utilizes EP steel to inhibit the distribution of nonmetallic inclusions in order to prevent subsurface originated flaking. The technology also utilizes TF technology to control the amount of retained austenite and degree of hardness in order to prevent surface originated flaking.[1)]

More recently, a newly identified type of flaking (white structure flaking) was occasionally found to affect pulley support bearings used b-CVTs and engine-driven accessory bearings, which operate under severe conditions. White structure flaking is classified neither as subsurface originated flaking nor surface originated flaking. Thus, NSK developed and commercialized several grease products (MA7, MA8 and HA1), which have proven to be effective in preventing the initiation of white structure flaking.[2)]

However, when bearings are used in oil-lubricated applications, such as b-CVTs for example, grease products are ineffective in preventing white structure flaking. In addition, since the operating conditions of engine-driven accessory bearings are expected to become even more severe, measures only using grease as described above may not prove effective. Therefore, an effective measure against white structure flaking must be sought from the perspective of bearing material. Unfortunately, the mechanism of white structure flaking was unclear, so no suitable bearing material could be identified.

With NSK's discovery that white structure flaking was induced by hydrogen, two new types of materials were developed: SHX3 surface-hardened steel and SHJ5 through-hardened steel. This article describes the mechanism of white structure flaking and discusses features of the newly developed materials.

2. Mechanism of White Structure Flaking

2.1 Factors of white structure flaking

White microstructures that appear white after etching can be observed in the maximum shear stress area near the flaking as shown in the example of Photo 1. In general, dark etching constituents (DEC), white etching constituents (WEC), and butterfly that appear near nonmetallic inclusions are known as microstructural alterations caused by bearing fatigue.[3)] These microstructural changes typically occur at a point far beyond calculated bearing life.[1)] However, the white structure flaking described earlier is generated in a short time—approximately one-tenth of the calculated life. The formation of white structure flaking also differs from that of conventional microstructural changes.

Previous research reported on various mechanisms of white structure flaking, including bending stress[3)] and plastic strain localization.[4)] Some recent studies report that bearing service life can be enhanced in the presence of white microstructures by changing grease additives,[5)] and has shown that white microstructures can be reproduced in a hydrogen gas environment,[6)] which proves that in some cases, white microstructures cannot be explained using only bending stress or plastic strain localization theories.

Since white microstructures can be reproduced in a hydrogen gas environment, a detailed examination was made focusing on hydrogen.

Initially, the amount of penetrated hydrogen was measured using a mass spectrometer, for bearings both with and without white structure flaking (Fig. 2). For the bearing with white structure flaking, a hydrogen peak was detected, which established the existence of penetrated hydrogen. For the bearing without white structure flaking, no hydrogen peak was detected, which confirmed the existence of penetrated hydrogen.

To clarify the influence of hydrogen, the amount of increased hydrogen was measured using a white structure flaking simulation test machine[7)] and a general rolling fatigue life test machine. The influence of the amount of penetrated hydrogen was determined from the ratio of

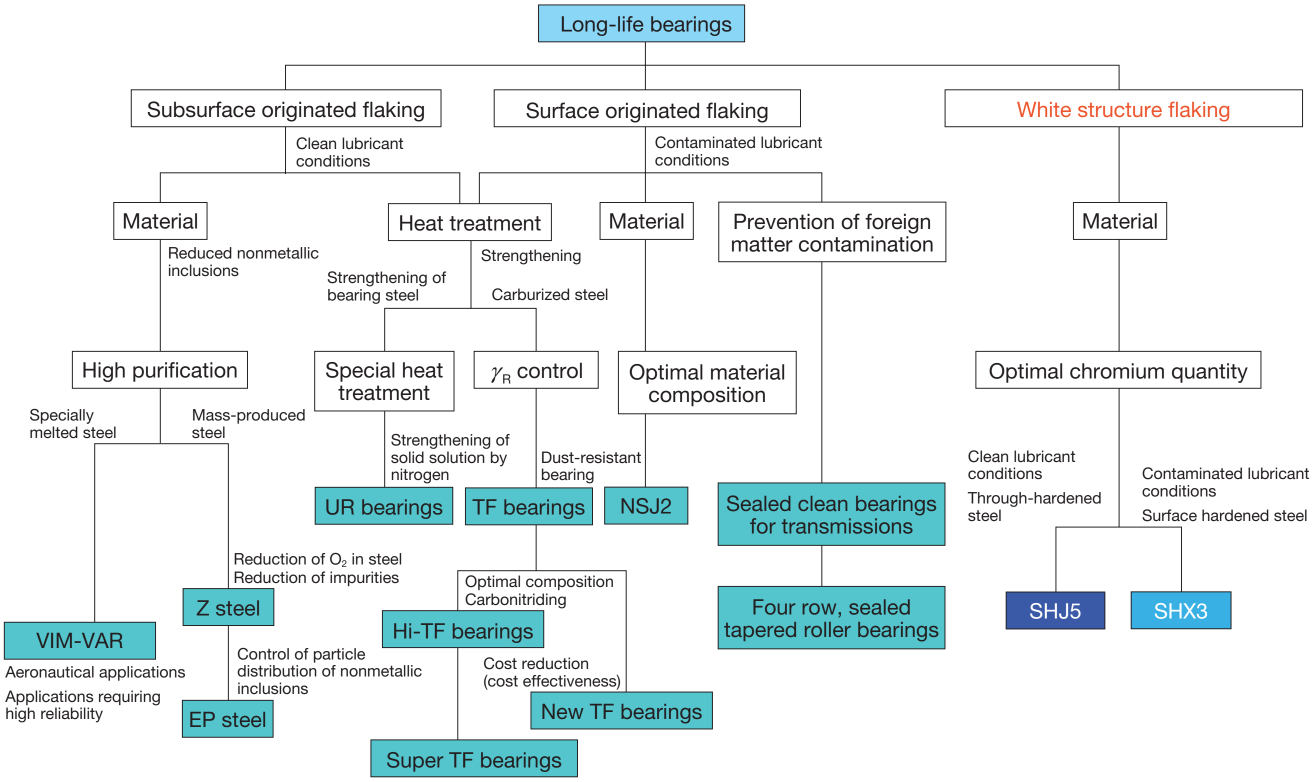

Fig. 1 An empirical approach to long-life material development

actual life to calculated life to eliminate varying test conditions. White structure flaking is not always generated at a certain amount of penetrated hydrogen, and thus no relationship to the amount of penetrated hydrogen was identified (Fig. 3). However, the hydrogen penetration rate was significantly different in accordance with the generation of white structure flaking. A high penetration rate of hydrogen was observed under conditions where white structure flaking was generated.[8)] Thus, the generation of white structure flaking is not determined by the absolute amount of hydrogen, but rather, it depends on the penetration rate of hydrogen into the bearing material.

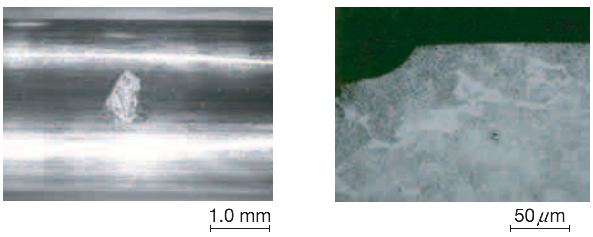

Photo 1 White microstructure (microscopic cracks) in the material of a failed bearing after actual use

2.2 Mechanism for achieving long life

As in the previous section, hydrogen was identified as the main factor causing white structure flaking. An examination of materials that resisted white structure flaking proved that the following measures are effective in achieving long life:

(1) Reduce the generation of hydrogen

Hydrogen is generated by decomposing lubricant when metal-to-metal contact between rolling elements and raceway surfaces form an activated surface.

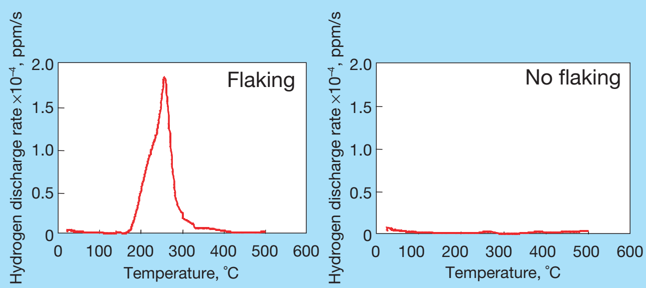

Fig. 2 Measured amounts of hydrogen in bearing material after life testing

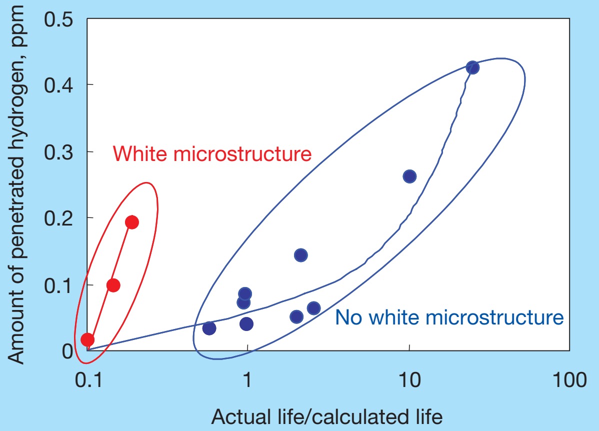

Fig. 3 Measured amounts of penetrated hydrogen in bearings after life testing

Therefore, reduce the formation of activated surfaces and the generation of hydrogen by improving the abrasion resistance of rolling surfaces by precipitating fine carbide and/or carbonitride.

(2) Reduce the concentration of hydrogen

White structure flaking tends to be generated when hydrogen penetrates into the bearing material and becomes concentrated a the maximum shear stress points.

Therefore, reduce the concentration of hydrogen by decreasing the diffusion rate of hydrogen by adding alloy elements.

Hydrogen is generated by tribochemical reactions of lubricant. The generated hydrogen moves toward and is absorbed into bearing surfaces, and then penetrates into bearing materials. The concentration of hydrogen at a fine defect in the maximum shear stress area locally weakens material strength. As a result of this process (Fig. 4), white structure flaking is generated.

Investigation results of the bearing steel composition revealed that by increasing chromium content in bearing steel, we were able to reduce the diffusion rate of hydrogen (Fig. 5). In fact, 13Cr steel effectively reduces the amount of penetrated hydrogen (Fig. 6).

A rolling fatigue life test was then carried out. The test bearings contained various amounts of chromium added to SAE 52100 as the base material, and were charged with hydrogen in advance to reproduce white structure flaking. Increasing chromium content ensured longer life performance and greater resistance to white structure flaking (Fig. 7). Life test results proved that bearing material containing chromium is effective in achieving longer life (Fig. 8) by preventing hydrogen from penetrating and diffusing in bearings and from concentrating at microscopic cracks, material imperfections, or metallic grain boundaries.

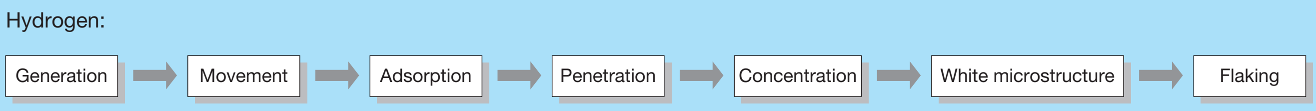

Fig. 4 Process of white structure flaking

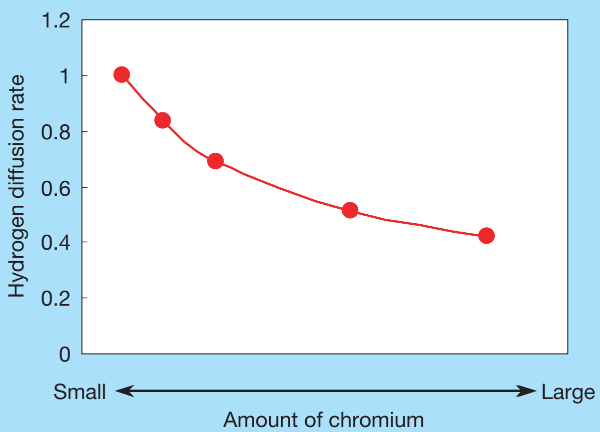

Fig. 5 Relationship between chromium content in steel and rate of hydrogen diffusion

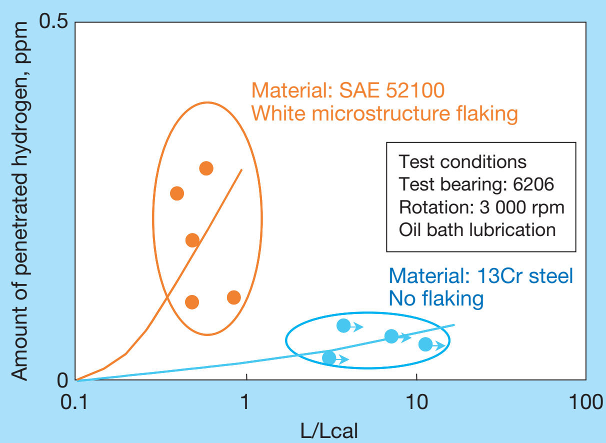

Fig. 6 Measured amounts of penetrated hydrogen in bearings after life testing

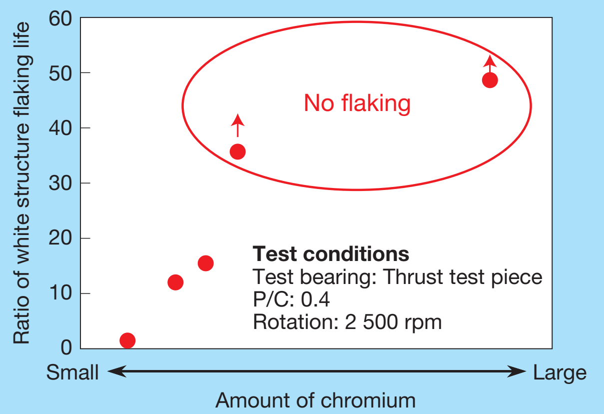

Fig. 7 Relationship between chromium content in steel and white structure flaking

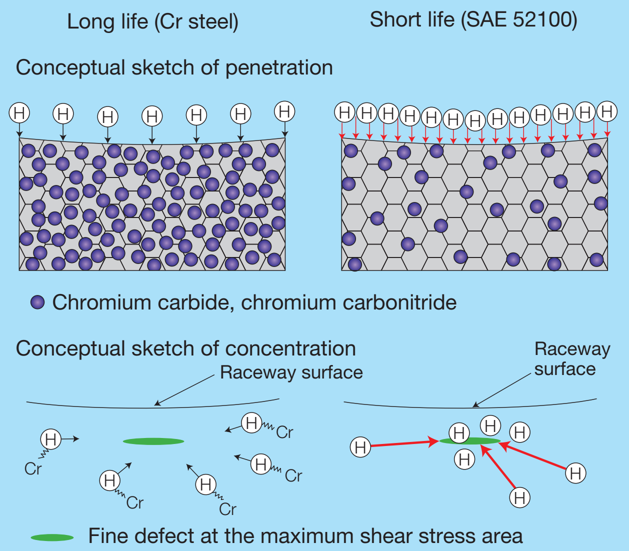

Fig. 8 Using chromium as a means of achieving long life

3. Features of Long-Life Materials

Features of SHX3 steel for applications operating under contaminated lubricant conditions and SHJ5 steel for applications operating under clean lubricant conditions are described below.

3.1 Contaminated lubricant conditions (surface hardened steel: SHX3 steel)

3.1.1. Concept for achieving long life

Bearings for automotive b-CVTs, automatic transmissions, and manual transmissions are used under contaminated lubricant conditions. When bearings are used in such environments, surface originated flaking is generated sequentially as shown in Fig. 9: (1) Entry of foreign matter → (2) Formation of indentations on the rolling surface → (3) Stress concentration at the indentation edge → (4) Generation of cracks → (5) Generation of flaking. Less stress concentration produces smaller indentations and a rounder indentation edge. Increasing hardness of the rolling surface effectively reduces indentation size, whereas increasing the amount of residual soft austenite (γ_R) effectively rounds the shape of the indentation edge. In order to simultaneously achieve these conflicting characteristics, NSK developed TF technology,[1] which

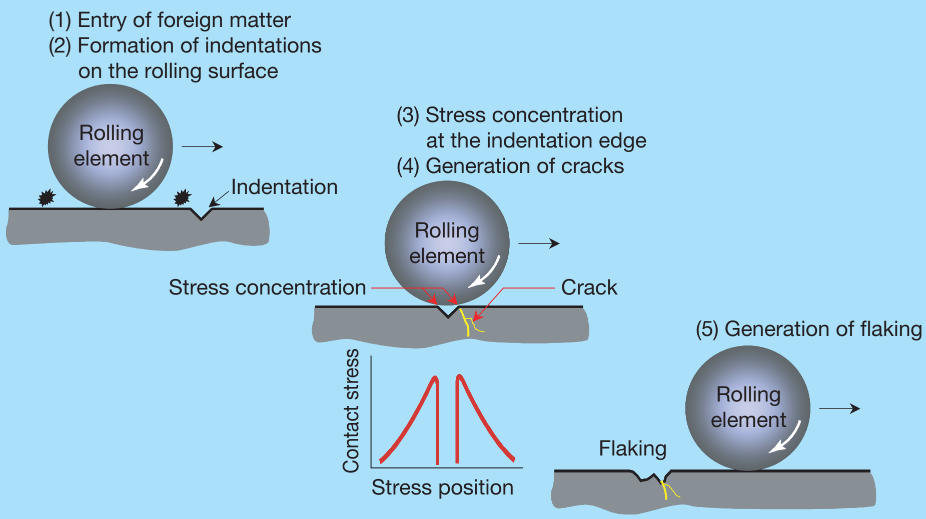

Fig. 9 Mechanism of surface-originated flaking

increases residual austenite without compromising hardness by precipitating a large quantity of fine carbonitride.

SHX3 steel is a type of surface hardened steel with an appropriate quantity of chromium added to a base of SAC steel[2] using TF technology.

3.1.2 SHX3 life test results

In general, simply performing a life test does not generate white structure flaking; however, appropriate test conditions were selected to reproduce white structure flaking, including testing under oil lubricating conditions.

As shown in Fig. 10, SHX3 steel has a service life that is ten times longer than that of SAE 52100 and five times long than that of HTF under conditions where white structure flaking is present. In the presence of surface originated flaking, SHX3 has a service life that is five times longer than that of SAE 52100 under contaminated lubricant conditions (Fig. 11). SHX3 has a service life that is twice that of SAE 52100 under subsurface originated flaking and clean lubricant conditions (Fig. 12). Furthermore, SHX3 has a service life that is three times longer than that of SAE 52100, and longer than that of HTF (see figure 13, even under low oil film parameter conditions).

3.2 Clean lubricant conditions (through-hardened steel: SHJ5 steel)

3.2.1 Concept for achieving long life

SHJ5 steel, which consists of a chromium and through-hardened steel (similar to SAE 52100) composition, can be used for bearing material if the bearings will be used in a

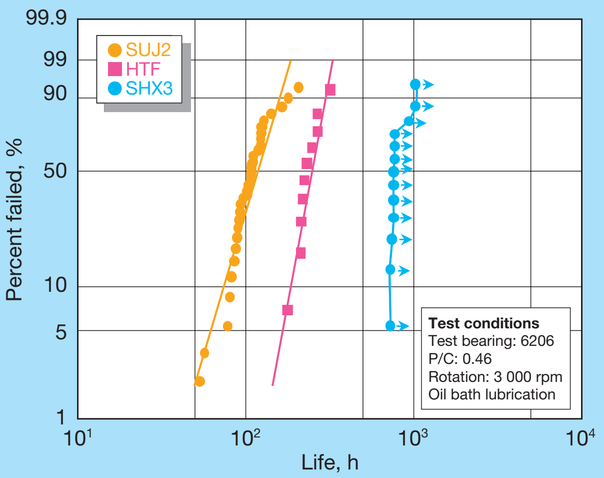

Fig. 10 Rolling fatigue life under hydrogen-induced flaking

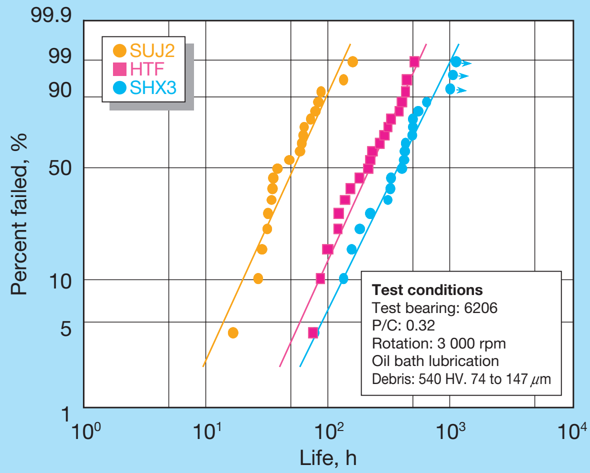

Fig. 11 Rolling fatigue life under contaminated lubricant conditions

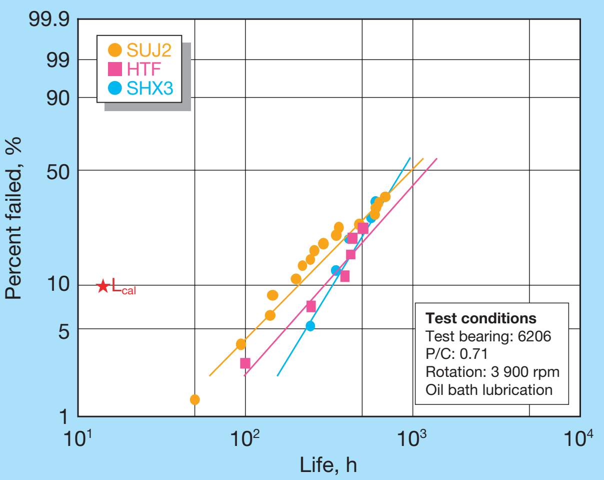

Fig. 12 Rolling fatigue life under clean lubricant conditions

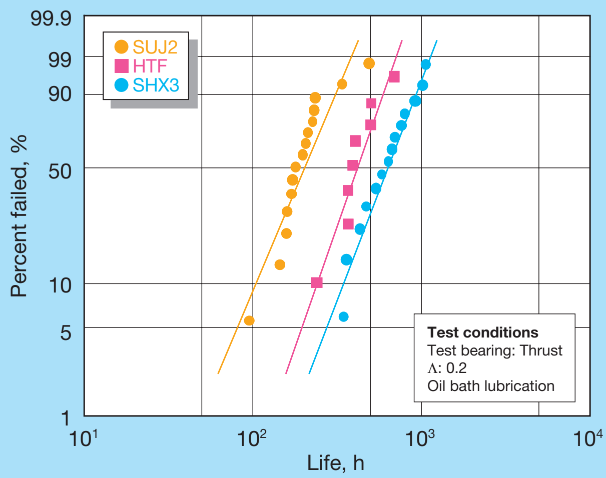

Fig. 13 Rolling fatigue life under low oil film parameter (oil film thickness/surface roughness ratio) conditions

clean environment that will not likely lead to the development of surface originated type flaking. Cost effectiveness (lower heat treatment costs) is the primary advantage of SHJ5 steel.

3.2.2 SHJ5 life test results

Testing was conducted in a clean environment with grease lubrication.

SHJ5 steel has a service life that is four times longer than that of SAE 52100 under conditions where white

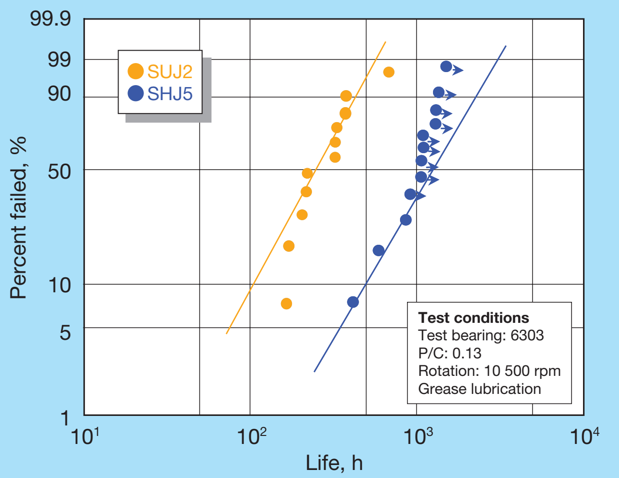

Fig. 14 Rolling fatigue life under hydrogen-induced flaking

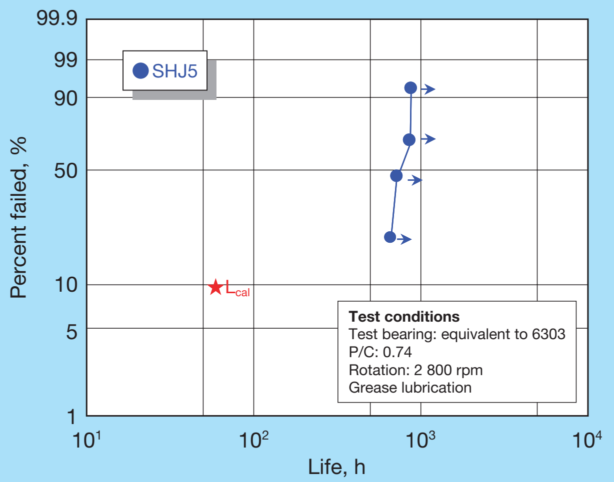

Fig. 15 Rolling fatigue life under clean lubricant conditions

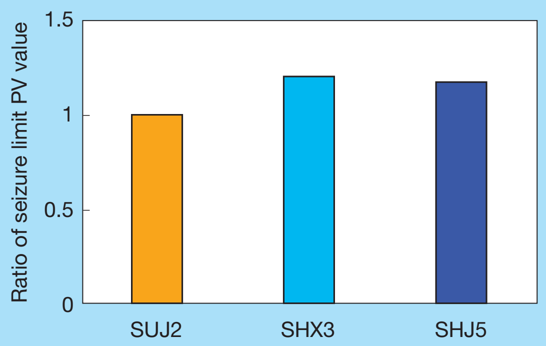

Fig. 16 Seizure limit test results for each material

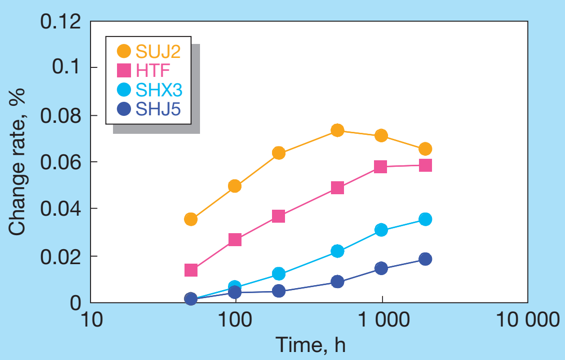

Fig. 17 Dimensional stability of each material

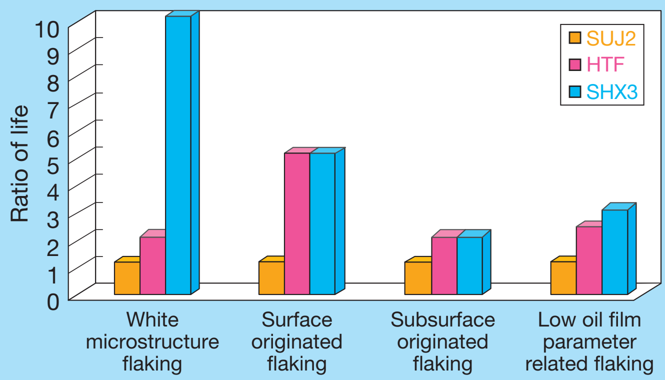

Fig. 18 Rolling fatigue life of SHX3 steel

structure flaking is present (Fig. 14). In comparison to calculated life under conditions where subsurface originated flaking is present, SHJ5 has a service life that is ten times longer (Fig. 15).

3.3 Material properties

Since an appropriate quantity of chromium is added to both SHX3 steel and SHJ5 steel, they exhibit low heat conductivity, which may cause bearings to seize. However, the measured seizure limit PV value for both types of steel proved that they deliver better performance than SAE 52100 (Fig. 16). They also exhibit better dimensional stability than SAE 52100 (normal heat treatment), and can be used in high-temperature applications (Fig. 17).

4. Conclusion

NSK developed two new types of bearing steel material—SHX3 surface hardened steel and SHJ5 through-hardened steel—by increasing chromium quantity to the greatest extent possible while focusing on the penetration rate of hydrogen.

Results of the rolling life test for SHX3 are summarized in Fig. 18. The rolling life test for SHJ5 showed that service life while operating in the presence of white structure flaking is four times longer than that of SAE 52100, and has a comparable service life to that of SAE 52100 while operating in the presence of subsurface originated flaking.

Both SHX3 steel and SHJ5 steel not only exhibit excellent fatigue resistance while operating in the presence of white structure flaking, but also satisfy other service life requirements for bearings.

NSK will continue to propose promising new technologies that meet evolving market needs and will further establish basic technologies that support the ongoing development of the automobile industry.

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New Products

High Performance Series —HPS™ Spherical Roller Bearings

The high-load capacity, self-aligning capability (to compensate for misalignment), and easy-to-handle non-separable design make NSK's spherical roller bearings most suitable for a variety of applications including iron and steel works, pulp and paper mills, mining machines, and construction machinery. These types of industries demand that bearings provide improved running performance and durability. The EA series was NSK's response to these demands back in 1998. Although the EA series enjoyed a favorable reputation in the global marketplace, NSK made significant performance-related improvements with the HPS series of spherical roller bearings. This article introduces the features of this new series of bearing (Photo 1).

1. Features

HPS spherical roller bearings provide users with the following features:

(1) Longer life

Optimization of the bearing's internal design, the application of new processing technologies, and quality-enhance bearing material have all been combined to manufacture a new bearing product that achieves higher load capacity and a longer service life that is twice that of conventional NSK products (Fig. 1).

(2) Higher limiting speed

A specialized surface treatment applied to the pressed steel cages achieves significantly improved wear resistance that is at most 1.2 times higher than that of conventional bearings.

(3) Higher limit temperature

A specialized treatment (standard specification) is applied to the inner and outer rings to ensure dimensional stability even under high-temperature conditions up to 200°C.

(4) Machined lubrication groove and oil hole

Both conventional spherical roller bearings and the HPS series have a machined lubrication groove and oil hole as a standard specification to meet various lubricating requirements including grease lubrication, oil bath lubrication, and forced-circulation oil lubrication.

2. Applications

HPS spherical roller bearings will be introduced with the following three series and forty-two bearing numbers with an outside diameter ranging from 80 mm to 260 mm (Table 1).

- 22208-22226
- 22308-22324
- 21308-21318

This assortment of series and bearing numbers will be made available to meet the needs of most industrial applications with sizes ranging from compact to very large. Two types of standard bearing clearance will be made available: normal and C3. All bearings will be made available with a cylindrical bore and a tapered bore as a standard specification.

Photo 1 HPS™ spherical roller bearings

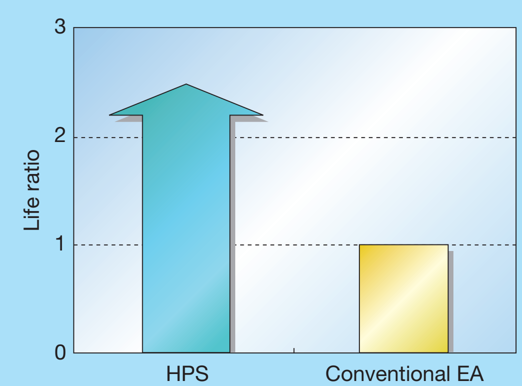
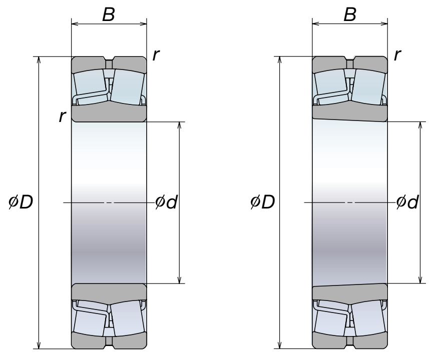


Fig. 1 Fatigue life test results

3. Summary

HPS spherical roller bearings are the latest high-performance standard roller bearing and available for a wide range of applications including those that traditionally required exclusive bearings. NSK will continue to further develop products that are readily available to satisfy customer needs.



Cylindrical bore   Tapered bore

Table 1 Bearing table of HPS™ spherical roller bearings

Bearing number		Boundary dimension (mm)				Basic load rating		Limiting speed (rpm)	
Cylindrical bore	Tapered bore	*d*	*D*	*B*	*r* (minimum)	C_r (N)	C_{0r} (N)	Grease lubrication	Oil lubrication
22208EAE4	22208EAKE4	40	80	23	1.1	113 000	99 500	6 700	8 500
21308EAE4	21308EAKE4	40	90	23	1.5	118 000	111 000	6 000	7 500
22308EAE4	22308EAKE4	40	90	33	1.5	170 000	153 000	5 300	6 700
22209EAE4	22209EAKE4	45	85	23	1.1	118 000	111 000	6 000	7 500
21309EAE4	21309EAKE4	45	100	25	1.5	149 000	144 000	5 000	6 300
22309EAE4	22309EAKE4	45	100	36	1.5	207 000	195 000	4 500	5 600
22210EAE4	22210EAKE4	50	90	23	1.1	124 000	119 000	5 600	7 100
21310EAE4	21310EAKE4	50	110	27	2	178 000	174 000	4 500	5 600
22310EAE4	22310EAKE4	50	110	40	2	246 000	234 000	4 300	5 300
22211EAE4	22211EAKE4	55	100	25	1.5	149 000	144 000	5 300	6 700
21311EAE4	21311EAKE4	55	120	29	2	178 000	174 000	4 500	5 600
22311EAE4	22311EAKE4	55	120	43	2	292 000	292 000	3 800	4 800
22212EAE4	22212EAKE4	60	110	28	1.5	178 000	174 000	4 800	6 000
21312EAE4	21312EAKE4	60	130	31	2.1	238 000	244 000	3 800	4 800
22312EAE4	22312EAKE4	60	130	46	2.1	340 000	340 000	3 600	4 500
22213EAE4	22213EAKE4	65	120	31	1.5	221 000	230 000	4 300	5 300
21313EAE4	21313EAKE4	65	140	33	2.1	264 000	275 000	3 600	4 500
22313EAE4	22313EAKE4	65	140	48	2.1	375 000	380 000	3 200	4 000
22214EAE4	22214EAKE4	70	125	31	1.5	225 000	232 000	4 000	5 300
21314EAE4	21314EAKE4	70	150	35	2.1	310 000	325 000	3 200	4 000
22314EAE4	22314EAKE4	70	150	51	2.1	425 000	435 000	3 000	3 800
22215EAE4	22215EAKE4	75	130	31	1.5	238 000	244 000	4 000	5 000
21315EAE4	21315EAKE4	75	160	37	2.1	310 000	325 000	3 200	4 000
22315EAE4	22315EAKE4	75	160	55	2.1	485 000	505 000	2 800	3 600
22216EAE4	22216EAKE4	80	140	33	2	264 000	275 000	3 600	4 500
21316EAE4	21316EAKE4	80	170	39	2.1	355 000	375 000	3 000	3 800
22316EAE4	22316EAKE4	80	170	58	2.1	540 000	565 000	2 600	3 400
22217EAE4	22217EAKE4	85	150	36	2	310 000	325 000	3 400	4 300
21317EAE4	21317EAKE4	85	180	41	3	360 000	395 000	3 000	4 000
22317EAE4	22317EAKE4	85	180	60	3	600 000	630 000	2 400	3 200
22218EAE4	22218EAKE4	90	160	40	2	360 000	395 000	3 200	4 000
21318EAE4	21318EAKE4	90	190	43	3	415 000	450 000	2 800	3 600
22318EAE4	22318EAKE4	90	190	64	3	665 000	705 000	2 400	3 000
22219EAE4	22219EAKE4	95	170	43	2.1	415 000	450 000	3 000	3 800
22319EAE4	22319EAKE4	95	200	67	3	735 000	780 000	2 200	2 800
22220EAE4	22220EAKE4	100	180	46	2.1	455 000	490 000	2 800	3 600
22320EAE4	22320EAKE4	100	215	73	3	860 000	930 000	2 000	2 600
22222EAE4	22222EAKE4	110	200	53	2.1	605 000	645 000	2 600	3 200
22322EAE4	22322EAKE4	110	240	80	3	1 030 000	1 120 000	1 900	2 400
22224EAE4	22224EAKE4	120	215	58	2.1	685 000	765 000	2 400	3 000
22324EAE4	22324EAKE4	120	260	86	3	1 190 000	1 320 000	1 700	2 200
22226EAE4	22226EAKE4	130	230	64	3	820 000	940 000	2 200	2 600

Long-Life Bearings for Push-Belt CVTs —BELTOP™ Bearings

The biggest structural difference between a push-belt continuous variable transmission (belt CVT) and a manual or automatic transmission is that the power is transmitted from an input shaft to an output shaft through a metal belt in combination with a pulley. Bearings that support the pulley shaft are primarily designed to a special specification in order to meet the specific requirements of a CVT. Since the operating condition of such bearings is different from that of a conventional transmission, previously unheard of problems began to manifest themselves in these bearings. Photo 1 illustrates some of the damage found, which includes premature flaking accompanied by white microstructures and microscopic cracks.

NSK was able to determine that hydrogen-induced flaking was the cause of such premature deterioration. In response to this greater understanding about the flaking mechanism, NSK developed long-life pulley-support bearings, which are marketed as BELTOP bearings (Photo 2). Information related to the features and performance of the BELTOP bearing is described in this article.

1. Features

(1) NSK's original high-chromium casehardened steel (SHX3)
a. By precipitating and dispersing highly hardened

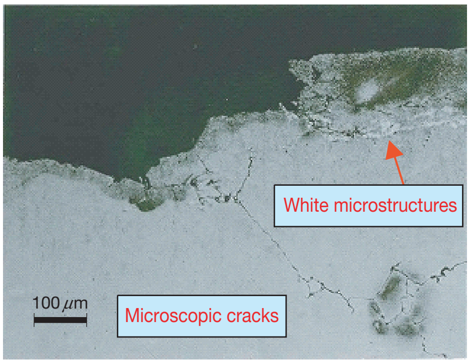


Photo 1 Example of premature flaking (occurrence of white microstructures and microscopic cracks)

Photo 2 BELTOP™ bearings

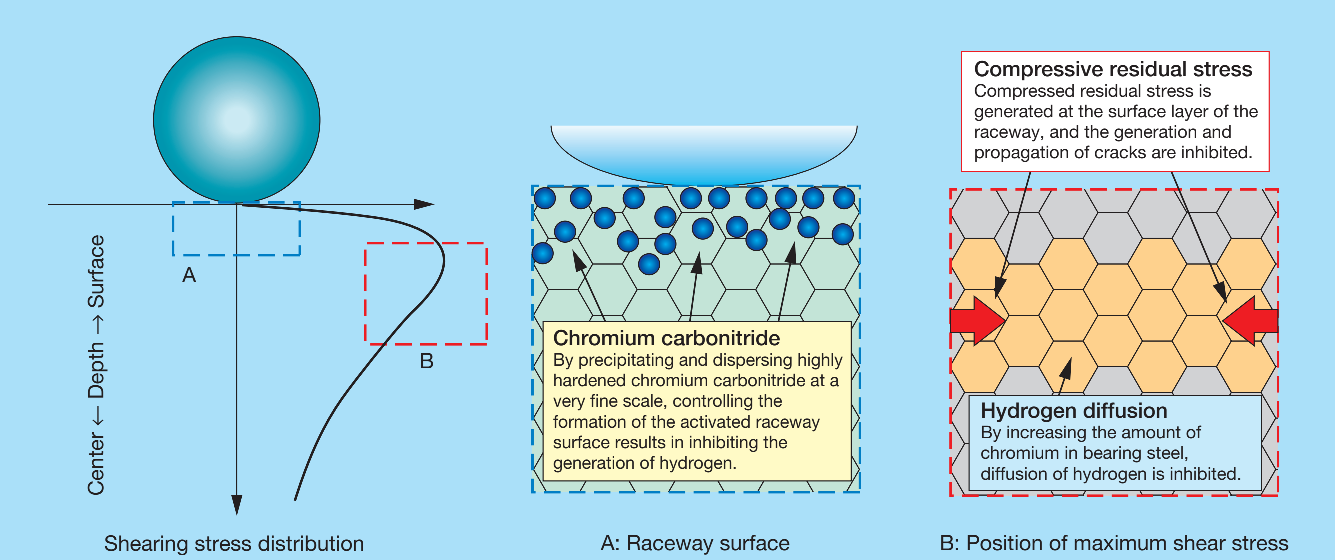


Fig. 1 Effectiveness of NSK's originally developed bearing steel (SHX3)

chromium carbonitride at a very fine scale, wear resistance is improved so that controlling the formation of the activated raceway surface results in inhibiting the generation of hydrogen by decomposing lubricant (Fig. 1).

b. Increasing the amount of chromium in the bearing steel results in greater control over the rate of hydrogen diffusion and protects against maximum shear stress where hydrogen has invaded the material, which results in the generation of white microstructures and microscopic cracks (Fig. 1).

(2) Carbonitriding technology

a. Compressive residual stress is generated by carbonitriding heat treatment on the raceway surface layer, which helps control the generation and propagation of cracks.

b. A significant amount of fine carbonitride particles are precipitated evenly, and retained austenite increases without a decrease of hardness (TF technology). Stress concentration at the circumference of an indentation, which is generated on the raceway surface by debris, is also mitigated.

2. Performance

(1) This product has 10 times longer life than bearings made of SAE 52100 steel against flaking caused by hydrogen (Fig. 2).

(2) This product has five times the fatigue life of conventional SAE 52100 steel bearings for contaminated environments (Fig. 3).

(3) Dimensional stability under high-temperature operating conditions is more favorable than conventional SAE 52100 steel bearings (Fig. 4). The change in dimensional accuracy due to high-temperature is less than conventional SAE 52100 steel bearings.

3. Summary

As belt CVTs become more compact with a higher load capacity, the operating conditions of the support pulley pair shafts will also become harsher. This creates conditions where flaking with the generation of white microstructures and microscopic cracks would normally increase.

NSK took the initiative and was quick to clarify the mechanism of hydrogen-induced white microstructure generation. This resulted in the development of BELTOP bearings, which offer longer life by helping to inhibit the penetration of hydrogen into bearing steel, and work to control the concentration of hydrogen already in the steel.

BELTOP bearings will be added to the lineup of other NSK products in the UR family of bearings using SAE 52100 steel and carbonitride treatment in addition to the Hi-TF series of bearings that use originally developed steel and TF technology for belt CVTs. NSK offers a complete lineup of long-life bearings for belt CVTs that meet the various needs of customers and their belt CVT applications.

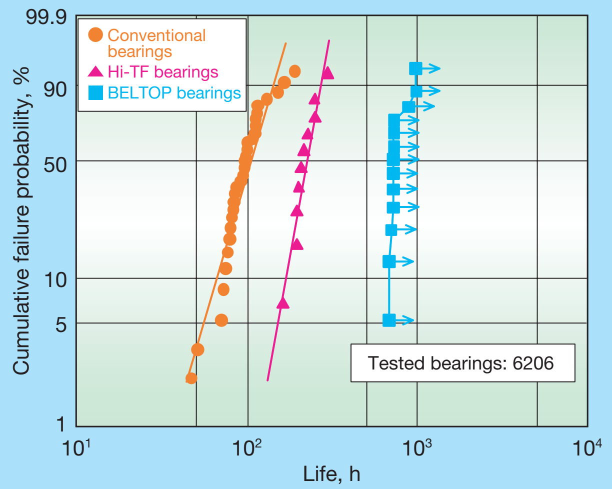


Fig. 2 Life test results of hydrogen-induced fatigue

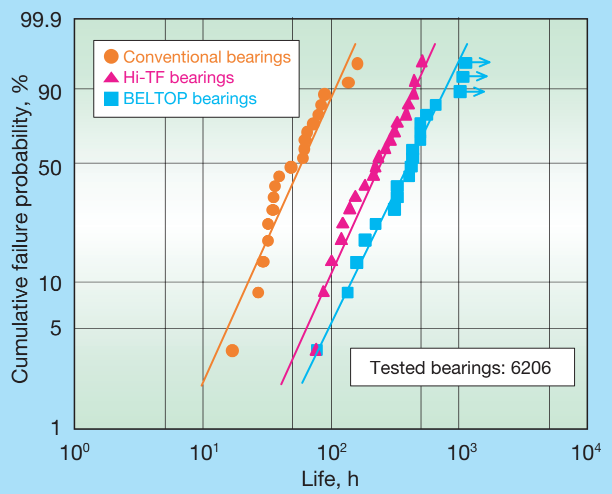


Fig. 3 Bearing life under contaminated lubricant conditions

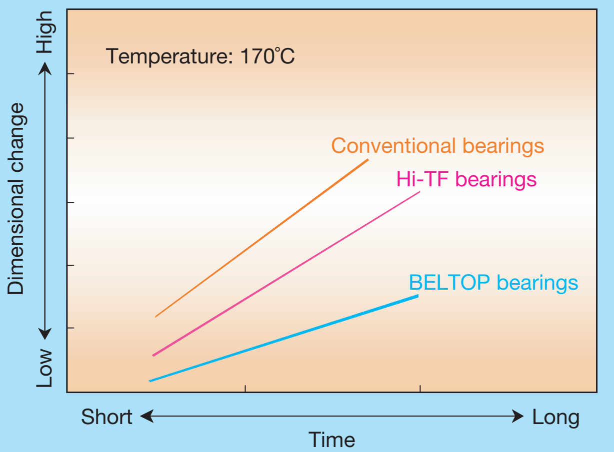


Fig. 4 Dimensional stability under high-temperature operating conditions

Creep-Resistant Outer Ring of Automotive Transmission Bearings

Automotive transmission bearings occasionally suffer from damage that is caused by a phenomenon called outer ring creep where the outer ring slightly rotates in relation to the transmission case (aluminum housing) during operation. Conventional measures consist of restricting outer ring movement with the use of a pin or flange (Fig. 1), in addition to the application of a solid lubricant coating to the outer ring exterior surface to help prevent transmission case wear. Unfortunately, these measures are both time consuming and cost prohibitive. After considerable effort, NSK successfully clarified the mechanism of outer ring creep in transmission bearings and developed a cost-effective and efficient method for preventing outer ring creep. This article introduces details regarding this new product.

Photo 1 Anti-creep bearings and standard bearings

1. Specification

1.1 Preventing outer ring creep

The outer ring of NSK's anti-creep bearing is thicker than that of conventional bearings (Photo 1). This design helps to minimize the generation of creep by reducing elastic deformation, which is the real cause of creep.

• Mechanism of outer ring creep generation

NSK has clarified the mechanism of creep by numerical simulation using FEM analysis (details to be reported in another issue of Motion & Control). Analysis results revealed that outer ring creep is generated by continuous expansion and contraction motion generated at the outside surface of the outer ring when load, which is generated under the force of gear engagement, is applied to the bearing.

1.2 Optimum design

Various test results and numerical simulation using FEM analysis were put to use in designing both the outer ring and bearing specifications. The result of an optimum design is a bearing that can prevent outer ring creep in order to achieve longer life performance and can offer higher load capacity.

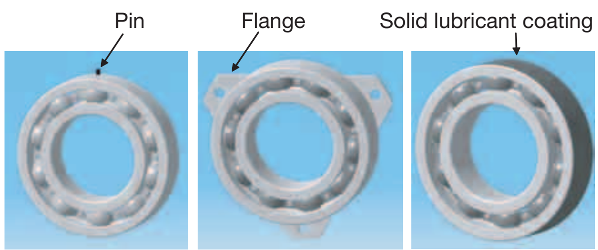


Fig. 1 Conventional measures to counter outer ring creep and transmission case wear

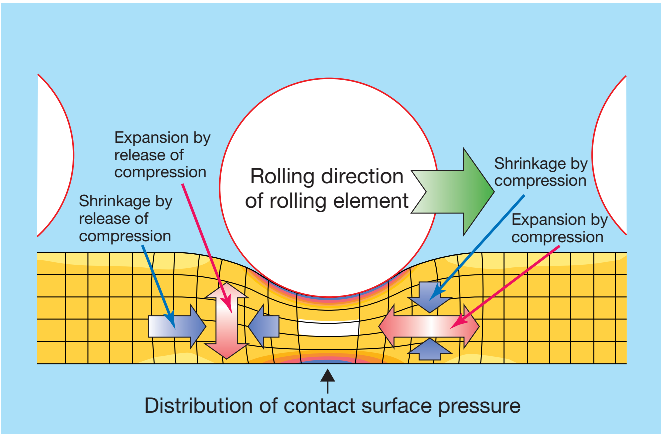


Fig. 2 FEM analysis

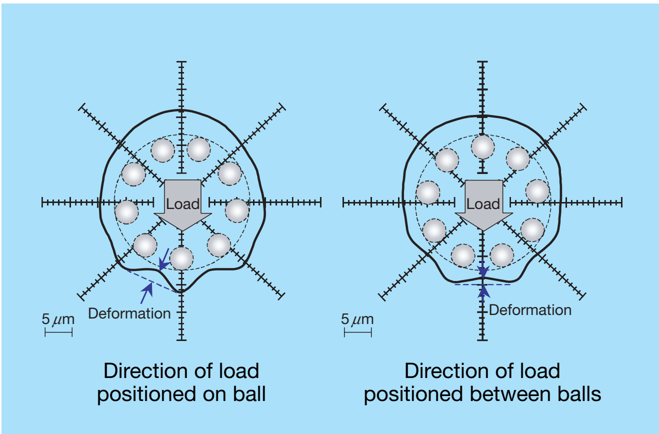


Fig. 3 Roundness of outer ring under loaded condition

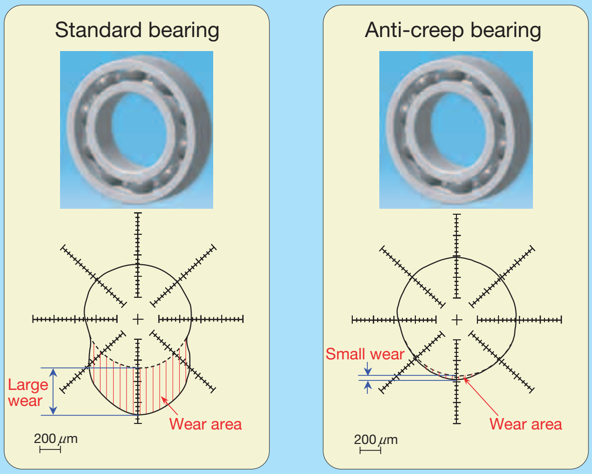


Fig. 4 Test results of transmission case wear for standard bearing and anti-creep bearing

2. Anti-Creep Bearing Features

2.1 Highly effective

Measures taken to increase outer ring rigidity (increased thickness of the outer ring) ensure the anti-creep effectiveness of the bearing. The degree of effectiveness was confirmed in wear tests where transmission case wear of the case bore surface of anti-creep bearings was smaller than that of standard bearings (Fig. 4).

2.2 Easily mounted

Whereas this anti-creep bearing has no specialized parts and is free of any special surface coatings, mounting of the bearing is extremely easy and can be done without any special tools or handling requirements. Thus, transmissions built with these anti-creep bearings can be assembled quicker due to the simplified design.

2.3 Superior performance

Through the application of design optimization tools, we have been able to develop a product that helps prevent outer ring creep and helps to ensure superior performance in transmission applications, which require bearings that offer long life, high load capacity, low friction torque, and are highly rigid.

3. Application

The design optimization process takes into consideration each bearing specification, such as the cross section of the outer ring, to assist in creating a product design that also incorporates operating conditions and bearing dimensions into the overall design. This process enables NSK to create bearings that meet the needs and requirement for a wide range of operating conditions. The design optimization process is just as effective in designing bearings for other applications besides automotive transmission. If another application also suffers from similar creep, we believe that the design optimization process can be a valuable tool in preventing such creep.

4. Summary

The NSK anti-creep bearing offers superior performance over that of conventional products. We believe that this bearing can fulfill our customer's expectations. We will continue to promote product developments that respond to needs of users in the market.

Lip-Guided (LG) Thrust Needle Roller Bearings

Increasing the rotational speed of the output shaft while restricting the input speed of the engine has been cited as one means of improving fuel efficiency in an automatic transmission. This means of improving fuel efficiency and the application of other fuel efficient technologies has resulted in a trend where an increasingly number of transmission components are being operated at much higher speeds than ever before. Consequently, thrust needle roller bearings used in transmission components are operated at increasingly higher speeds as well. In response to such high-speed operating conditions, NSK has developed and commercialized a new type of thrust needle roller bearing that uses a cage with improved wear resistance (Photo 1).

1. Features of the LG Thrust Needle Roller Bearing:

(1) High rotational speed

Improvements of the roller end face and the cage pockets where the roller ends make contact have been made to increase wear resistance of the cage. The result is a thrust needle roller bearing that operates at twice the speed (relative rotation) of conventional bearings.

(2) Low frictional torque

The configuration mentioned earlier also contributes to reducing frictional torque, which is the sliding resistance that is generated between the roller end face and the cage pocket.

(3) Compact

A roller diameter of only 2 mm is a critical factor in achieving weight and size reductions of components and helps to reduce the overall length of the transmission.

(4) Types

Two types of this bearing (cage & roller assembly type and unitized type with raceway washer) will be made available to meet the needs of customers.

2. Roller Specification

The roller end face of each roller in a thrust needle roller bearing is typically flat to accommodate low-profile requirements and smaller bearing sizes. However, under operating conditions of very high rotating speeds or extremely low loads, the cage pocket face may be damaged due to excessive wear as centrifugal force pushes the roller end face up against the contact point of the roller cage pocket. NSK took the following measures to address these issues:

(1) The roller end face was optimized by changing from a flat surface to a spherical shape.

(2) Conventionally, roller end faces were flat and made contact with the cage inner pocket along the outer circumference of the roller end face (Fig. 1). Under high-speed operations, however, these rollers suffered from excessive wear thus reducing their service life. In order to reduce wear, reduce frictional torque, and achieve longer life under increasingly harsh operating conditions, NSK adopted roller end face crowning for the rollers used in LG thrust needle roller bearings. Test results (Fig. 2) showed that the cage pockets were free of damage or wear when tested with rollers that had crowned roller end faces even when rotational speed was twice that of the conventional configuration, which had suffered some damage and excessive wear (Fig. 2 ; Photos 2 and 3).

Photo 1 LG thrust needle roller bearings

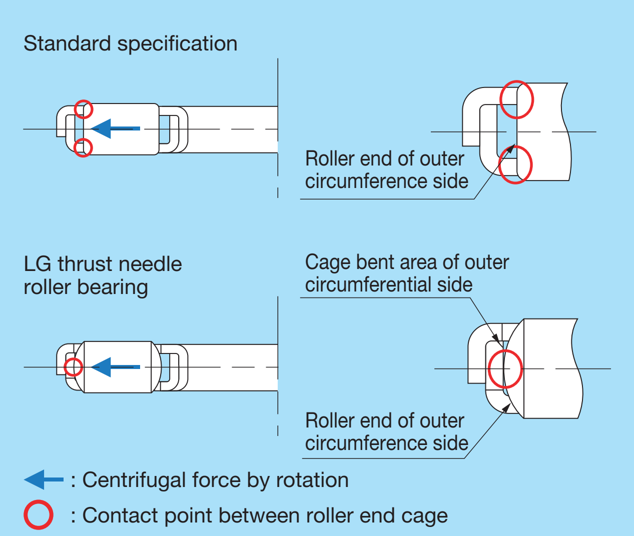
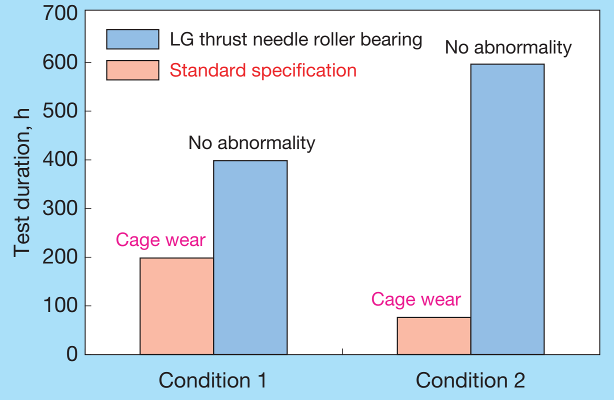


Fig. 1 Contact point of standard (top) and LG (below) thrust needle roller bearings



Test conditions
Condition 1 : Load 200 N Relative rotating speed 18 000 rpm
(Limiting speed ratio 2.8)
Condition 2 : Load 60 N Relative rotating speed 2 300 rpm
(Limiting speed ratio 2.5)

Fig. 2 Seizure test results

Photo 2 Wear of standard cage pockets

Photo 3 LG thrust needle roller bearings after test

3. Application

LG thrust needle roller bearings are used widely in automatic transmissions with planetary gear assemblies helical gears, push belt CVTs, and automatic transmissions used in hybrid vehicles.

4. Summary

As demand for vehicles with improved fuel efficiency grows, the need for LG thrust needle roller bearings will also increase. NSK will continue to develop new products to meet the needs of the market and to further improve vehicle performance.

Alternator Ball Bearings

As newer vehicles increasingly use sophisticated technologies, the burden placed on alternators also increases. The trend towards more compact alternators that operate at higher and higher speeds creates an operating environment that is becoming more severe with each passing year. During the 1980s, the outer ring of bearings used in alternators frequently suffered from premature flaking with white microstructures (microscopic cracks that develop into flaking). NSK solved the problem of flaking with its development of MA7 grease (see NSK Motion & Control Issue No. 4). Recently, however, there have been isolated cases where premature flaking occurred even in bearings using MA7 grease, which was likely due to the increasingly harsh operating conditions of alternators used in newer vehicles. NSK engineers addressed this issue by first clarifying the mechanism that results in the generation of premature flaking with white microstructural changes. Consequently, NSK developed new alternator bearings that are designed with measures to prevent premature flaking even under the harshest of operating conditions (Photo 1 and Fig. 1).

1. Bearing Specification

The process of premature flaking in the outer ring of alternator bearings was found to be caused by the intrusion of hydrogen into the bearing steel, which was generated by tribo-chemical reactions, and in turn formed a white etching constituent that generated flaking sooner than the end of calculated operational life (Fig. 2). Once NSK engineers understood this mechanism, they set about developing measures against premature flaking of alternator bearings, which included a new type of bearing grease and a new bearing steel material.

1.1 HAB grease

- Nanoscale carbon black particles are combined with HAB grease to create an electrically conductive grease.
- The electrically conductive HAB grease prevents the buildup of static electricity, which if present, would normally accelerate grease decomposition, which promotes the generation of hydrogen, and ultimately leads to the formation of white microstructures that cause premature flaking. Test results (Fig. 3) confirm the effectiveness of HAB grease.

Photo 1 Alternator ball bearings

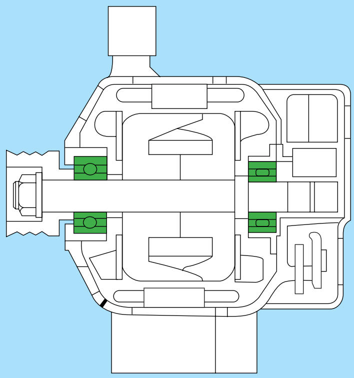


Fig. 1 Cross-section view of alternator

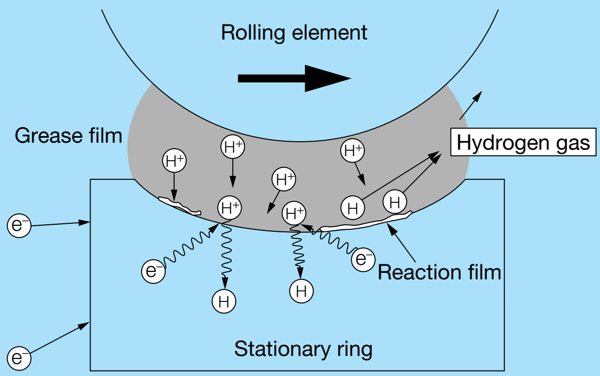


Fig. 2 Schematic diagram of hydrogen intrusion

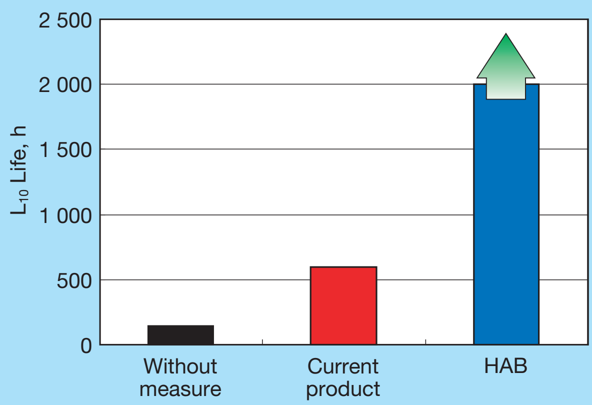


Fig. 3 White structure flaking durability test

1.2 Steel material (SHJ5, ES1)

- Fine dispersion of high hardness chromium carbide reduces abrasion of the raceway surface. inhibits the intrusion and diffusion of hydrogen.
- Improved wear resistance (reduced abrasion) inhibits the intrusion and diffusion of hydrogen in bearing material.

Table 1 lists the bearing specifications and Fig. 4 shows the life ratio test results.

Table 1 Bearing specifications

Bearing specifications	Current specification	Standard specification	Long life specification	Super long life specification
Bearing material	SUJ2	SUJ2	SHJ5	ES1
Grease	Conventional product	HAB	HAB	None specified

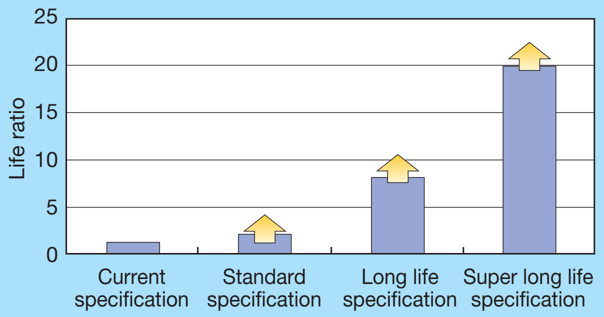


Fig. 4 Life ratio

2. Features

(1) Bearings using HAB grease combined with nanoscale carbon black particles ensure sufficient electrical conductivity and are more than twice as durable against white structure flaking than comparable products.

(2) The use of high chrome steel for the SHJ5 specification ensures a service life that is four times longer than SUJ2 steel, and ten times longer than SHJ5 steel for the ES1 specification. Furthermore, the high chrome steels offers excellent dimensional stability in high-temperature operating conditions.

3. Summary

NSK has successfully developed an alternator bearing that incorporates specific measures to mitigate the effects of premature flaking, which has been made possible by extensive research into the mechanism that results in the generation of premature flaking with white microstructural changes. We are confident that this new bearing will contribute towards extended maintenance-free intervals and reduced maintenance costs.

High-Strength Plastic Pulley Units

Automakers have increasingly demanded that suppliers reduce the weight of automotive components for improving fuel efficiency in their cars. Furthermore, automakers around the world are placing greater emphasis on engine accessories (alternators, compressors for air conditioners, etc.) that improve fuel efficiency and promote further downscaling of components. One response to this trend is to use resin material in manufacturing pulley units instead of steel.

The trend towards lightweight and compact designs has resulted in an environment where belt tensioner pulleys (idler pulleys) receive considerable load from the smooth backside of the serpentine belt , thus creating a harsh operating environment for the pulley unit. In response to customer needs and the increasingly harsh operating environment, NSK has developed a next-generation high-strength plastic pulley unit that offers improved strength over comparable products (Photo 1).

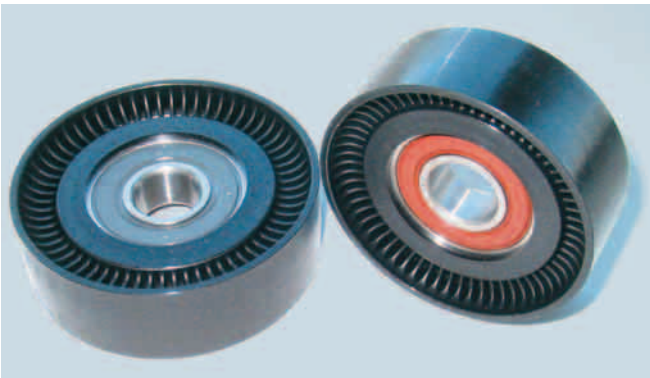


Photo 1 High-strength plastic pulley units

1. Features

The newly developed pulley unit incorporates changes in the plastic material and changes in the configuration of the unit, which combine to improve overall strength.

(1) High-strength plastic material was achieved by:
- optimizing the molecular mass of the base nylon material;
- optimizing the diameter of glass fibers that are then blended with the base nylon material; and
- modifying the glass fiber ratio to more closely meet requirements of plastic pulley operations.

These improvements have resulted in a high-strength plastic pulley unit that provides 70% more material rigidity and 45% more tensile strength in comparison to plastic pulley units made of conventional materials (Fig. 1).

(2) Pulley unit and bearing configuration

Investigation results from FEM analysis of stress generated in the plastic material were applied in designing an optimal configuration of the newly developed pulley unit and the pulley unit bearing. As a result, stress generated in the plastic material was reduced by 10%.

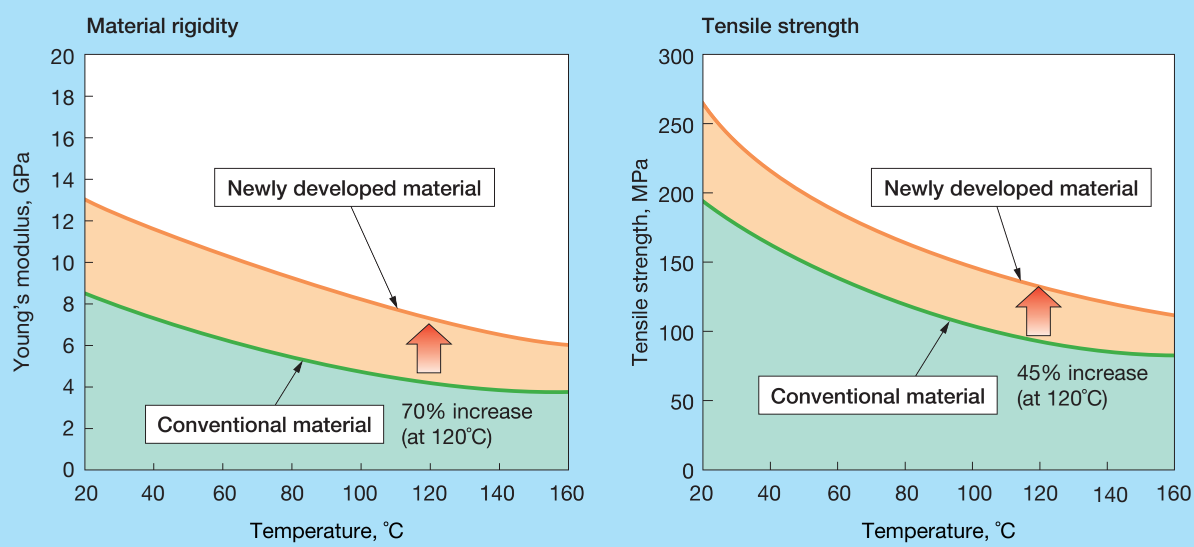


Fig. 1 Improved characteristics of newly developed material

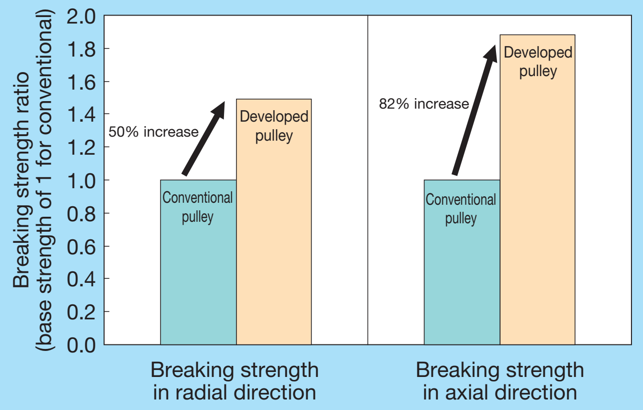


Fig. 2 Breaking strength test results

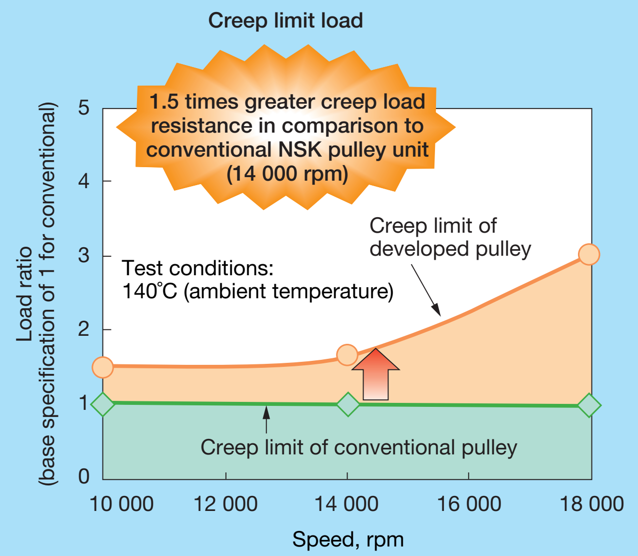


Fig. 3 Anti-creep performance

2. Performance

Pulley unit strength was increased significantly by adopting an improved plastic material and by optimization of the pulley unit configuration.

(1) Breaking strength

Breaking strength in the radial and axial directions was greatly improved over that of conventional products (Fig. 2).

(2) Anti-creep performance

Anti-creep performance was improved by one and half times that of the conventional NSK pulley unit (Fig. 3).

3. Summary

NSK's newly developed high-strength plastic pulley unit offers significant improvements that make this product ideal for automotive engine accessories that require superior performance under a wide range of loads and increasingly harsh operating conditions.

High-Speed and Low-Noise Ball Screws for Standard Stock—Compact FA Series

In 2003, NSK introduced the BSS series incorporating a new ball recirculation circuit, which offered users significantly higher speeds, quieter performance and in a smaller size than NSK products existing at that time. Since then, this series has been highly evaluated in the market for improving machine tool productivity, improving working conditions by reducing noise levels, and highly evaluated for saving space using a smaller ball nut diameter.

In 2005, NSK developed and commercialized the compact FA series, which joined the BSS series lineup of ball screws, as standard stock with exclusively designed low-profile support units (Photo 1).

Photo 1 Compact FA series and low-profile support units

1. Specifications

- New ball recirculation circuit provides high-speed and low-noise performance.
- Optimum preloading using oversized balls is adopted for saving space.
- Lead accuracy achieved under the specification of JIS grade C5, which offers a higher standard tolerance than ISO grade 5.
- Low-profile support units exclusively designed and commercialized for the compact FA series.
- 165 units available as standard stock for various combinations of shaft diameter, lead, and stroke (Table 1 lists the series lineup and combinations with recommended support units).

Table 1 Series lineup

Shaft diameter (mm)	Lead (mm)	Stroke (mm)														Recommended support unit	
		50	100	150	200	300	400	500	600	700	800	1 000	1 200	1 600	2 000	Fixed support side	Simple support side
10	5	●	●		●	●	●									WBK08-01B	WBK08S-01B
	10		●		●	●	●										
12	5	●	●		●	●	●	●								WBK08-01B	WBK08S-01B
	10		●		●	●	●	●									
	20		●		●	●	●	●									
	30		●		●	●	●	●									
15	5	●	●		●	●	●	●	●							WBK12-01B WBK10-01B	WBK12S-01B
	10		●		●	●	●	●	●	●	●	●					
	20		●		●	●	●	●	●	●	●	●					
	30		●		●	●	●	●	●	●	●	●					
20	5			●	●	●	●	●	●	●	●					WBK15-01B	WBK15S-01B
	10				●	●	●	●	●	●	●	●	●				
	20					●	●	●	●	●	●	●	●	●			
	30				●	●	●	●	●	●	●	●	●				
	40						●	●	●	●	●	●	●	●	●		
	60						●	●	●	●	●	●	●	●	●		
25	5			●	●	●	●	●		●	●	●				WBK20-01	WBK20S-01
	10					●	●	●	●	●	●	●		●			
	20							●	●	●	●	●	●	●	●		
	25							●	●	●	●	●	●	●	●		
	30							●	●	●	●	●	●	●	●		
	50							●	●	●	●	●	●	●	●		

2. Features

The compact FA series, which is excellent in every aspect of quality, cost performance, and delivery, features the following:

(1) Low noise

Fig. 1 shows measured noise levels compared with the existing FA series. A newly adopted ball recirculation circuit reduces noise by 6 dB for a quieter, gentler sound, by incorporating a deflector in the nut that smoothly scoops the balls in the direction of their movement.

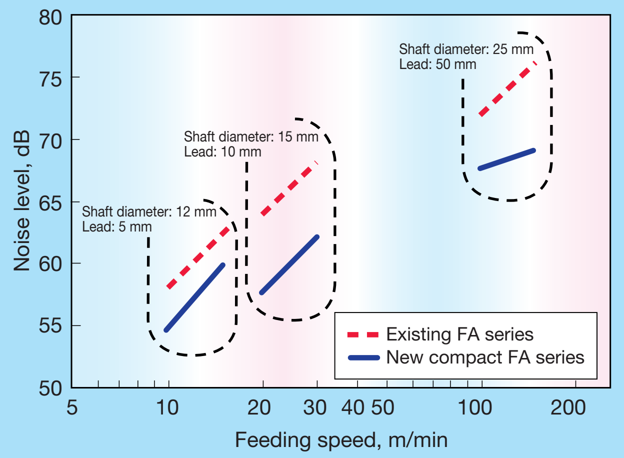


Fig. 1 Noise levels

(2) High speed

The new ball recirculation circuit enables rotational and feeding speeds that are 1.63 times faster than the existing FA series. The new units handle permissible rotational speeds up to 5 000 rpm compared to 3 000 rpm of existing FA series.

(3) Compact design

The new ball recirculation circuit also makes possible the use of a ball nut with an outside diameter that is as much as 30% more compact than the existing FA series. Combining the compact FA series with specially developed low-profile support units supports even more compact equipment, as well as a lower table center. Fig. 2 illustrates a comparison of both the existing FA series and the new compact FA series.

(4) Quick delivery

NSK maintains the compact FA series in standard stock along with the low-profile support units for prompt delivery.

3. Applications

The compact FA series is ideal for a variety of applications including semiconductor manufacturing equipment, LCD manufacturing equipment, chip mounters, measuring apparatus, and medical equipment.

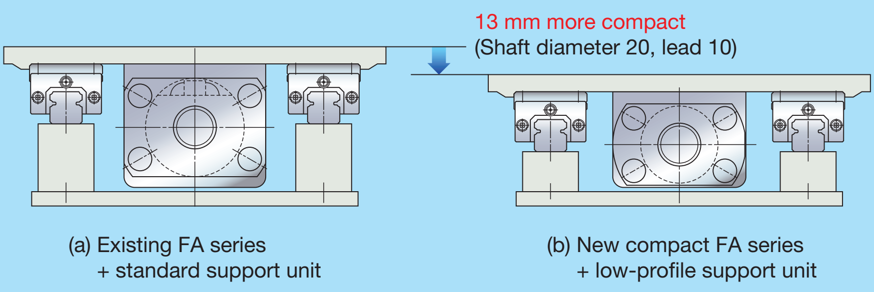


Fig. 2 Comparison of assembly height

Zero Backlash Joint

Cardan coupling assemblies for steering columns (commonly referred to as universal joints or U-joints) are mounted between the steering wheel and the steering gear at a specific angle to assist in transmitting torque. The growing demand for precise positioning in a steering system operating under high-speed conditions requires minimal side-to-side play (backlash) within the universal joint. To this end, NSK has recently commercialized a universal joint with backlash of nearly zero.

1. Construction

The basic structure of this new universal joint is the same as a conventional universal joint, which uses a conventional yoke and thrust piece. The use of a seal ring depends on the specific universal joint application (see Photo 1 and Fig. 1).

The close interference fit between the spider and the inscribed circle diameter of the bearing rollers achieves a torsional backlash of nearly zero. Conventional interference fit between the spider and the inscribed circle of bearing rollers can occasionally impact the smoothness of universal joint operation or increase torque (applied torque) during normal operation of the universal joint. Consequently, it was difficult to eliminate torsional backlash while simultaneously achieving good operational performance at the time of product development. A number of experiments were conduct in order to improve the design along with improvements that were made in the manufacturing process, which resulted in a solution to this problem.

Interference fit between the spider and the rollers increases the amount of surface pressure at the point of contact. Using FEM analysis and associated benchmark tests, an optimum fit allowance was determined.

Furthermore, development of a heat-resistant universal joint suitable for high-temperature operating conditions without any structural modification was possible as a result of the development of heat-resistant grease.

Torsional backlash is defined as the amount of clearance backlash or lost motion (see θ in Fig. 2) as a function of applied torque in bi-directional rotation and torque application. The slope of the line defines the torsional stiffness. The zero backlash joint exhibits almost no slope whatsoever, while the slope of the conventional product clearly illustrates lost motion or torsional backlash, which has a negative impact on steering precision.

Photo 1 Zero backlash joint

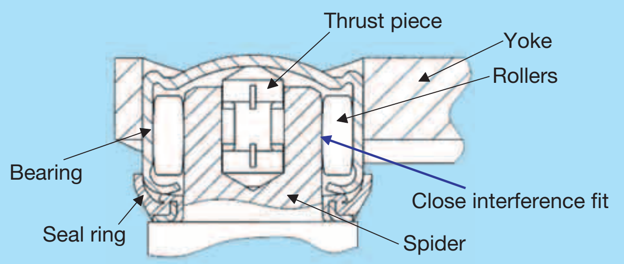


Fig. 1 Section of bearing area

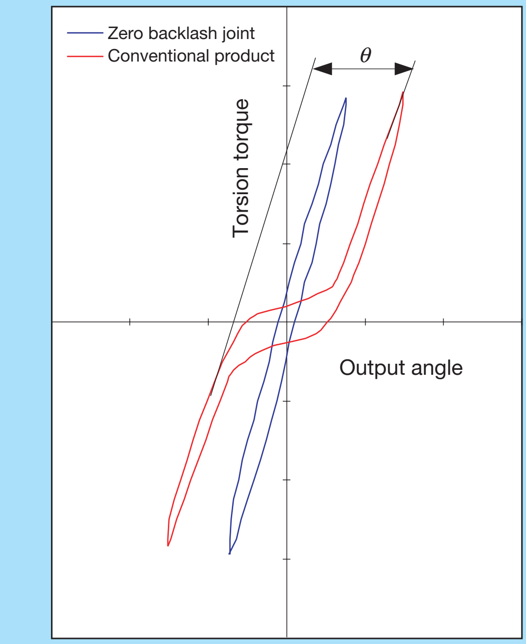


Fig. 2 Bidirectional results of clearance backlash

2. Advantages

2.1 Features and specifications

(1) Eliminating torsional backlash to nearly zero improves steering precision and reduces excessive play of the steering wheel when driving at high-speed. It also prevents the generation of rattling noise between the spider and the bearing. These advantages have been confirmed in practical vehicle tests and benchmark tests.

(2) The amount of applied torque in the new universal joint is slightly smaller than that of conventional universal joints despite achieving almost zero torsional backlash while offering good steering control.

(3) Water resistance is the same as that of the conventional universal joint.

(4) Rotating diameter is the same dimension as that of conventional units because the same yoke is used.

(5) A heat-resistant universal joint is available, which is applicable to a wide range of temperature conditions.

2.2 Strength

(1) Static torsional breaking resistance is the same as that of conventional universal joints, which have been well-received by the market for their proven strength (due to the structure and major component dimensions having not been modified).

(2) Durability is also the same as that of conventional universal joints, since the surface pressure at the contact point between the spider and the roller is appropriately adjusted.

2.3 Mass

Mass is the same as that of conventional universal joints because the major dimensions have not been modified.

2.4 Others

A conventional yoke can be applied without modification, regardless of geometry or manufacturing process (pressing, or hot or cold forging) resulting in a cost advantage.

3. Applications

Used in the steering systems of small vehicles and passenger cars.

4. Summary

There is a trend toward reducing torsional backlash in the steering systems of various types of vehicles for greater steering precision and responsiveness when driving at high speeds. The newly commercialized zero backlash joint meets this need and has been favorably evaluated by users. NSK is committed to continuing to develop products that satisfy user needs.

High-Power Column-Type Electric Power Steering

Because of growing environmental concern and greater social trends towards energy conservation, the demand for electric power steering (EPS) is increasing as an environmentally friendly technology. Accordingly, NSK has recently developed and marketed a high-power, high-performance, column-type EPS (Photo 1) for small to mid-size family cars.

1. System Overview

Figure 1 shows the construction of NSK's new column-type EPS system. The basic structure of this EPS system consists of a torque sensor that detects the level of force applied to the steering wheel by the driver, an electric control unit (ECU) that processes signals from the sensor to determine the appropriate level torque assist, a motor that generates the torque assist based on the ECU output, reduction gears that amplify and transmit torque from the motor to the steering wheel shaft, and a joint that transmits the amplified torque to the steering gear.

2. EPS Advantages

2.1 High power

- Changing from conventional brush-type motors to brushless motors increases output torque and reduces inertia.
- Optimized rectangular wave control further increases output and improves steering control.
- Whereas transmission torque was increased, the reduction gear and joint were strengthened.

2.2 Lightweight

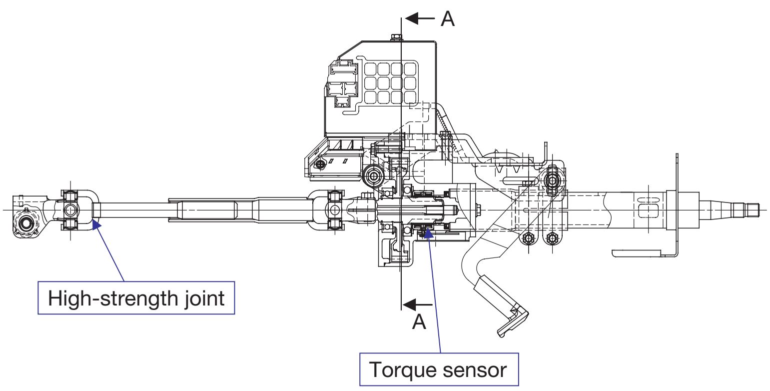
- To reduce weight, and in response to rising temperatures generated by a high current from the ECU, the heat sink and gearbox were combined as shown in Fig. 2.

2.3 High performance

(1) ECU: adopts a phase current comparator to offset compensation control.

To compensate for torque fluctuations due to variations in phase current that cannot be detected

Photo 1 Column-type EPS



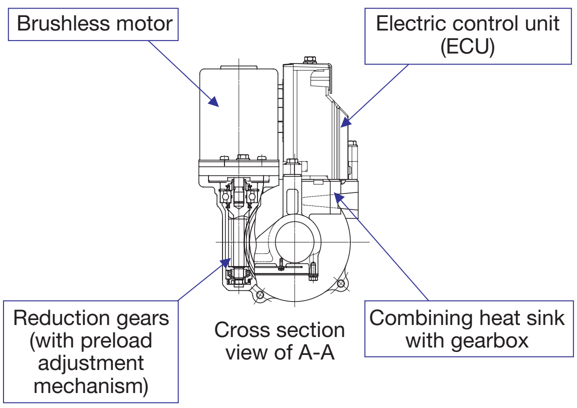


Fig. 1 Construction of column-type EPS

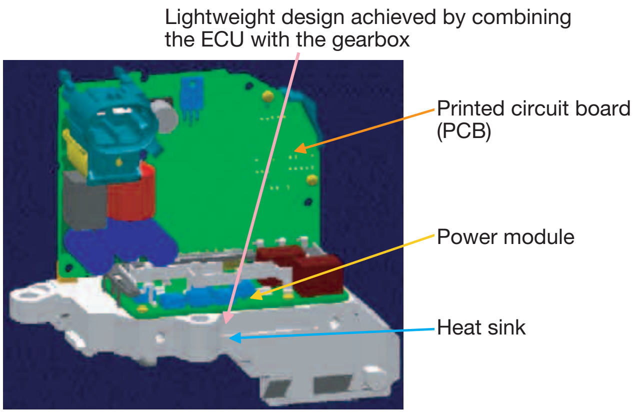


Fig. 2 ECU Structure

when a brush motor is used, additional drift control is adopted to ensure a natural steering feel.

(2) Brushless motor: reduces noise.

Noise levels when operating the steering wheel are reduced by optimizing rectangular wave control and by adopting brushless motors, wherein it has no rotating contact between the brush and the commutator, unlike brush-type motors.

(3) Reduction gear: reduces rattling noise

Applying spring-generated preload to both worm wheel and worm in the reduction gear reduces, rattling noise during operation (Fig. 3).

3. EPS Specifications

Table 1 shows the EPS system specifications.

4. Summary

NSK has commercialized a high-power, high-performance, column-type EPS for small to mid-size family cars. We are committed to promoting the use of future EPS systems in luxury vehicles by further improving high-power performance.

Table 1 EPS system specifications

Items		Details
Assembly	Assist torque	68 N·m
Reduction gear	Type	Worm and worm wheel
	Reduction ratio	(Wheel gear; injection molding) Two-thread
Motor	Type	3-phase brushless motor
	Rated current	95 A
	Rated speed	1 040 rpm
	Rated torque	4.20 N·m
	Position detection	Hall sensor
Torque sensor	Type	Non-contact, self-inductance
	Power supply voltage	DC9.5 V
Controller	Rated voltage	DC12 V
	Control range of motor current	0 – 95 A
	Communication functions	CAN
	Self-diagnosis & fail-safe functions	Initial check, Normal check (In case of detecting any failure, stores failure data in ECU)
	Control items	1) Phase compensation controller
		2) Robust stabilizing compensation controller
		3) Friction compensation controller
		4) Inertia compensation controller
		5) Yaw damping controller
		6) SAT feedback controller
		7) Drift compensation controller

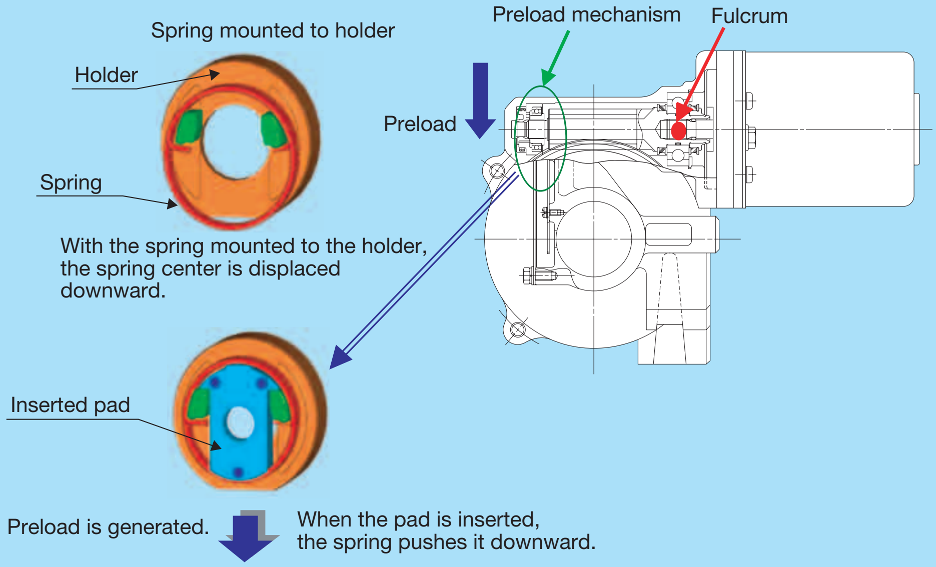


Fig. 3 Structure of preloaded reduction gear

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