Commentary

Introduction of Rolling Bearings for Electric Drives Corresponding of Automobiles

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Continued electrification of automobiles has introduced the need for electric drive bearings with new and diverse performance capabilities. This article introduces the efforts made at **NTN** to design rolling bearings specifically to meet these requirements.

1. Introduction

The automotive industry is undergoing an unprecedented transition from gas powered to fully electric vehicles. The shift to electric vehicles (EVs) is accelerating worldwide as one solution on the path to achieving carbon neutrality[1]. Rolling bearings, which support power transmission in electric drives, are a key component. They must respond to the demand for higher speeds in addition to smaller size, lighter weight, and lower torque. Here **NTN** introduces rolling bearings for electric drives that have been designed specifically to meet these requirements.

2. Performance Requirements of Rolling Bearings for Electric Drives

There are two main types of rolling bearings for automobiles: deep groove ball bearings and tapered roller bearings. These rolling bearings consist of the four parts shown in **Fig. 1** (inner ring, outer ring, rolling elements [balls and tapered rollers], and cage) and sometimes seals. With the recent shift to electric vehicles, bearings are required to have new performance characteristics to meet the operating conditions.

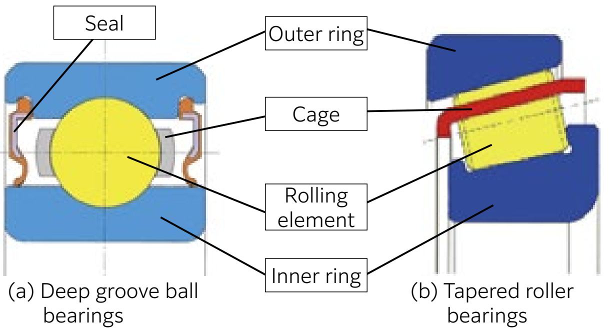

Fig. 1 Rolling bearing cross-section and part names[2]

Fig. 2 shows an example of an "e-Axle". An e-Axle is a drive unit which integrates a motor, inverter, and reduction gear for electric vehicles (EVs). An e-Axle with a parallel three-axis structure uses two bearings for the motor and six bearings for the gear reducer. **Fig. 3** shows a typical example of a parallel triaxial e-Axle with a rolling bearing arrangement supporting the motor and reduction gearbox. Since the combination of the motor torque and reduction ratio affects the bearing load on each axis of the reducer, deep groove ball bearings and tapered roller bearings are used on the second and third axes, depending on the load.

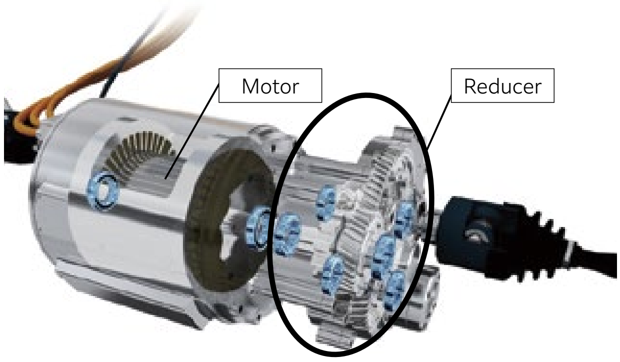

Fig. 2 Example of e-Axle structure and arrangement of rolling bearings[3]

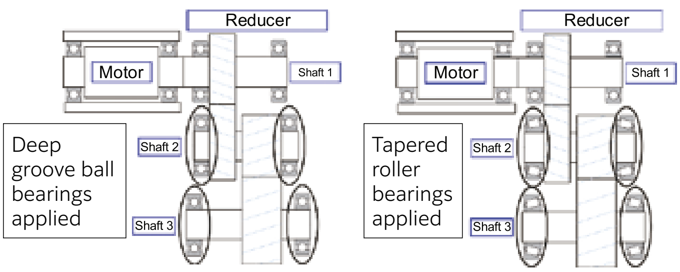

Fig. 3 Example of rolling bearing arrangement in a simplified cross-sectional view of an e-Axle (motor and reduction gear)[4]

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The rolling bearings used in each of the e-Axle's axes are required to have the following performance characteristics.

(1) To meet the demands for higher power output and downsizing of the e-Axle, driving motors are operating at higher speeds. The deep groove ball bearings that support the motor shaft and the directly connected motor shaft of the first reducer shaft are required to offer high-speed performance.
(2) As bearing raceways become thinner due to the e-Axle becoming smaller, creep (a sliding phenomenon in which the outer ring rotates relative to the housing) is more likely to occur on the outer diameter of the outer ring. Each reduction gear shaft must therefore have anti-creep measures.
(3) The high voltage of the batteries used in e-Axle motors requires countermeasures against electrical pitting of the bearings (a phenomenon in which electrical discharge occurs in the bearing, causing microscopic melting of the raceway surface) in the motor shaft and the first shaft of the reduction gear.
(4) To improve the efficiency of the e-Axle under low viscosity lubricating oil, the tapered roller bearing supporting the second shaft of the reducer requires heat generation countermeasures at the area of sliding contact on the large end rib.
(5) The increased bearing load associated with the higher output of the e-Axle requires the tapered roller bearings supporting the second and third shafts of the reducer to have a higher load carrying capacity than conventional bearings.

Table 1 summarizes the performance requirements for e-Axle rolling bearings.

Table 1 Performance Requirements for e-Axle rolling bearings

Market trend	Technology trends	Performance requirements for rolling bearings
Environment ally friendly technology Motor-driven electrification Shared	Higher efficiency	Low torque 3.1 Deep groove ball bearing with ultra-low friction seal 4.1 Low temperature rise and low torque tapered roller bearing
	Higher speed	Support for high-speed 3.2 Deep groove ball bearing for high-speed rotation
	Downsizing and lightweighting	Improved creep resistance 3.3 Creepless bearings
	Higher voltage Higher frequency	Preventing electrical pitting 3.4 Ceramic rolling element deep groove ball bearings
	Lower viscosity and smaller volume of lubricating oil	Lower temperature rise 4.1 Low temperature rise and low torque tapered roller bearings
	High reliability	Long operating life 4.2 Tapered roller bearings with long operating life

3. Introduction of high-performance deep groove ball bearings

This section introduces the technology **NTN** has developed for deep groove ball bearings to meet the performance requirements for e-Axles as shown in **Table 1**.

3.1 Deep groove ball bearing with ultra-low friction seal

Due to increased demand for higher efficiency and more compact e-Axles, the deep groove ball bearings used in these applications are required to have both high operating life and low operating torque. Optimizing e-Axle bearing operating life requires preventing hard particulate material present in the lubricating oil of the application from contaminating the bearing rolling surfaces. Although contact seals can prevent the intrusion of particulate contamination, it is difficult to optimize both bearing life and operating torque with this seal type because sliding torque (which accounts for most of the running torque for deep groove ball bearings with contact seals) is generated at the contact area between the seal lip and the inner ring.

NTN's newly developed ultra-low friction seal[5) employs a contact-type seal with arc-shaped (half-cylindrical shaped) microscopic convexes at equal intervals on the sliding contact area of the seal lip, as shown in **Fig. 4**. During rotation, the wedge film effect of the microscopic convexes forms an oil film **(Fig. 5)** between the sliding surfaces of the seal and inner ring, significantly reducing seal drag torque compared to a more conventional contact-type seal. Furthermore, because the clearance between the seal and the inner ring sliding surface is extremely small, the intrusion of particulate contamination of a size that would affect bearing operating life can be prevented.

Under the conditions shown in **Table 2**, **NTN** compared running torque between the ultra-low friction seal and conventional contact/non-contact seals. As shown in **Fig. 6**, The running torque of the ball bearing with ultra-low friction seals was 80 % lower than that of the ball bearing with contact seals due to the wedge film effect of the micro convexes on the seal lip. Running torque of the ball bearing with ultra-low friction seal was also equivalent to that of the ball bearing with non-contact seals.

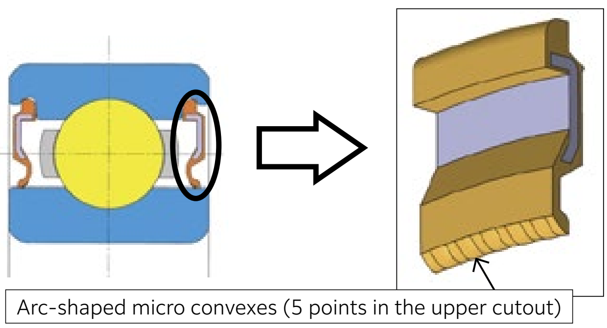


Fig. 4 Cross section of deep groove ball bearing with ultra-low friction seal[5)

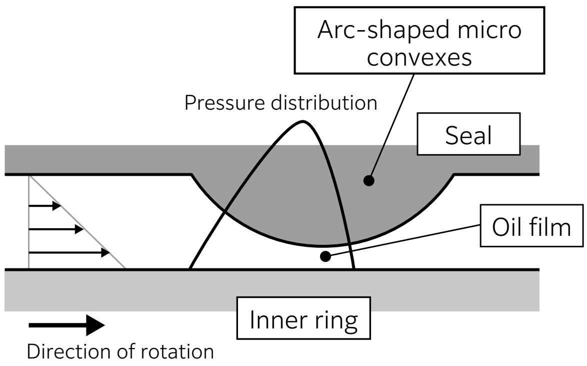


Fig. 5 Diagram of wedge film effect[5)]

Table 2 Test condition[5)]

Test bearing	6010 equivalent
Radial load	Basic dynamic load rating of 5 % (JIS B 1518:2013)
Rotational speed	1 500 min^{-1}
Bearing temperature	35 to 120 ˚C
Lubricating oil	CVTF

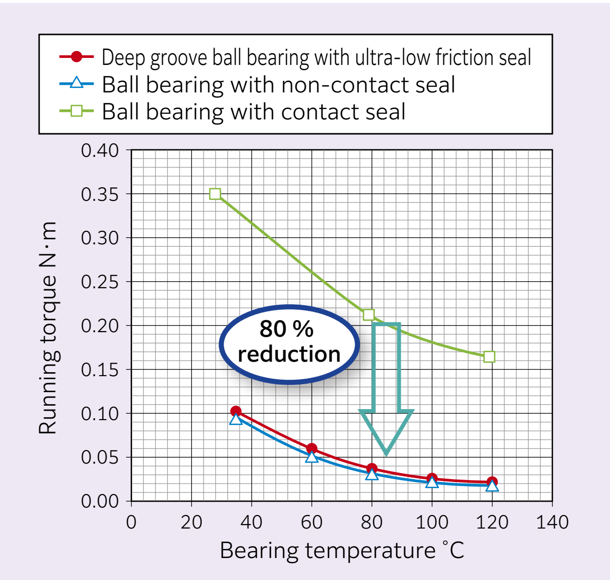


Fig. 6 Relationship between running torque and bearing temperature[5)]

3.2 Deep groove ball bearing for high speeds

By adopting a new shape of resin cage that takes into account the deformation of the cage during high-speed rotation, **NTN** found operation was possible under oil lubrication at $d_m n^{*1}$ = 180 × 10^4. Here **NTN** introduces a high-speed deep groove ball bearing for EV/HEV that uses high-speed rotation technology.[6) 7)]

*1 Bearing rolling elements pitch diameter and rotational speed mm min^{-1}

Deep groove ball bearings, which support the motor shaft of e-Axles and the directly connected motor of first axis reduction gears, are required to support high rotational speeds. As the rotational speed of deep groove ball bearings increases, centrifugal force causes contact between the cage pockets of the resin cage and the rolling elements (balls), which may result in seizure.

In response to this, **NTN** developed high-speed deep groove ball bearings for EVs and HEVs by adding improvements (1-4) to the resin cage.

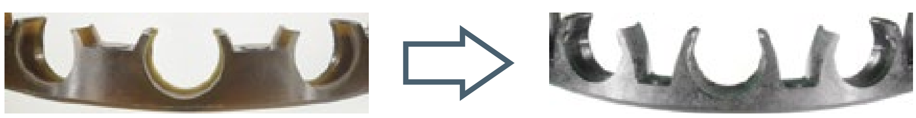
Fig. 7 shows a comparison between the conventional and improved resin cage.

(1) Adoption of high-strength materials
⇒ Improved rigidity and strength of cage
(2) Thickening of the pocket bottom to suppress deformation
⇒ Improved rigidity of cage ring
(3) Thinned wall between cage pockets (weight reduction)
⇒ Reduction of centrifugal force deformation
(4) Installation of oil grooves on the inner surface of the cage pockets
⇒ Improved lubricity of cage and rolling elements

A temperature rise qualification test (oil lubrication) was conducted on high-speed deep groove ball bearings for EVs and HEVs under the conditions shown in **Table 3**. **Fig. 8** shows the test results. The outer ring temperature of the high-speed deep groove ball bearings could be operated stably below the upper temperature limit for $d_m n$ values up to 180 × 10^4.

Table 3 Test condition[2)]

Tested bearing characteristics	Basic dynamic load rating = 16 800 N (JIS B 1518:2013)
Radial load	264.5 N
Axial load	147 N
Rotational speed	$d_m n$ 160 to 180×10^4



(a) Conventional resin cage (b) Modified resin cage

Fig. 7 Exterior of resin cage for high-speed deep groove ball bearings for EV/HEV[4)]

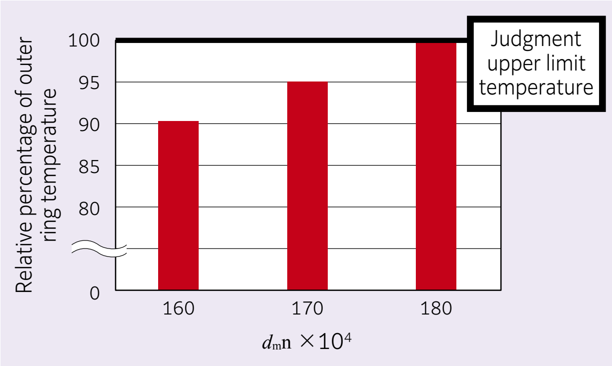


Fig. 8 Relationship between d_mn and outer ring temperature[2)]

Recently, by optimizing the lubrication conditions and the internal elements of the bearing, **NTN** has confirmed that the deep groove ball bearing can support high-speed rotation with a d_mn value of 220 × 10[4 8)].

3.3 Creepless bearing[9)]

As bearing raceways become thinner due to the demand for smaller and lighter e-Axles, the rigidity of the outer ring decreases, increasing the likelihood of rippling deformation on the outer ring outer diameter surface as the rolling element passes through. This repetition results in a progressive wave that causes the outer ring to rotate relative to the housing (progressive wave type creep).[10)]

The structure of the creepless bearing that **NTN** has developed is shown in **Fig. 9**. As shown in **Fig. 10**, by providing a full-width arc-shaped relief area on a portion of the outer ring outer diameter surface, the housing inner diameter surface and outer ring outer diameter surface lose contact when the undercut of the outer ring is positioned in the load-bearing zone, thereby blocking the transmission of traveling waves. This suppresses creep. Although creep occurs when the undercut of the outer ring is positioned in the non-load-bearing zone, creep stops at that position when the undercut of the outer ring moves to the load-bearing zone. Therefore, when the bearing is assembled into the housing, there is no need to align the undercut with the load-bearing zone. The only design change is in the undercut of the outer ring outer diameter, making it easy to replace an existing bearing.

Creep rate evaluation tests were conducted on creepless bearings and standard deep groove ball bearings[11)] under the conditions shown in **Table 4** in a testing machine for inducing creep. The test results are shown in **Fig. 11**. The creep rate of the standard deep groove ball bearing tended to increase with increasing load. By contrast, it was confirmed that creep did not occur in the creepless bearing under any of the loading conditions due to the effect of the outer ring undercut.

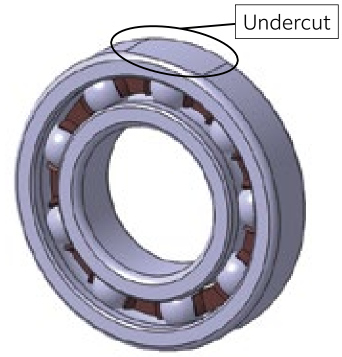


Fig. 9 Cross section of creepless bearings[9)]

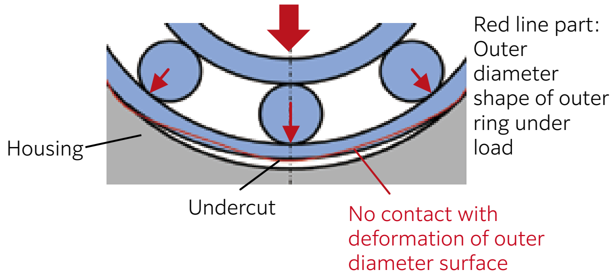


Fig. 10 Relationship between creepless bearing outer ring shape and housing[9)]

Table 4 Test condition[9)]

Bearing number	6208
Radial load	Basic dynamic load rating (JIS B 1518:2013) 10 % - 40 %
Inner ring rotational speed	6 000 min^{-1}
Lubricating oil	CVTF
Bearing outer ring temperature	50 ℃

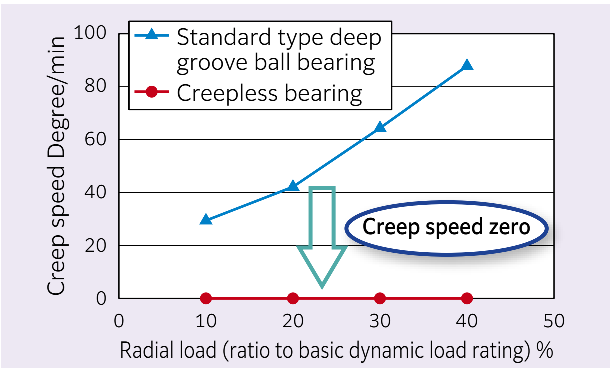


Fig. 11 Creep speed evaluation test results[9)]

3.4 Ceramic rolling element deep groove ball bearings

Fig. 12 Ceramic rolling element deep groove ball bearings

Inverter-driven motors are shifting toward higher power output and smaller size, and the drive power supplies are becoming higher voltage. In the case of inverter drives, a potential difference is generated between the shaft and housing. The oil film that forms between the bearing raceways and rolling elements is known to break down, causing damage due to electrical discharge. [12) 13)] The higher the voltage, the greater the potential difference generated, which increases the risk of bearing damage due to dielectric breakdown. This leads to acoustic deterioration and a shorter operating life. As a countermeasure, a ceramic rolling element deep groove ball bearing **(Fig. 12)** using silicon nitride ceramic balls as rolling elements can be applied to insulate the inner and outer ring raceways and prevent the occurrence of electrical pitting.

Rolling tests were conducted under the conditions shown in **Table 5** on the test machine shown in **Fig. 13** to investigate bearing spalling life in an energized environment. The results are shown in **Table 6**. Compared to standard ball bearings using steel balls, the ceramic rolling element deep groove ball bearing can suppress the occurrence of spalling on the rolling element surface due to electrical pitting.

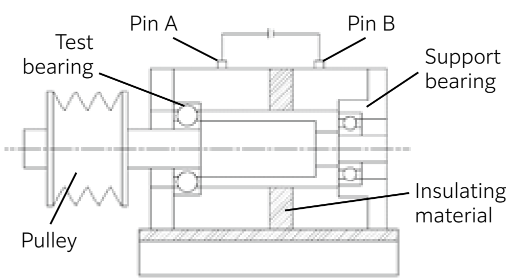


Fig. 13 Rolling life test machine

Table 5 Test condition[14)]

Bearing being tested	Deep Groove Ball Bearing (6203)	
Rolling element	Steel ball	Ceramic ball
Grease	Non-conductive grease	
Amount of grease injected (g)	0.86	
Rotational speed (min^{-1})	0-20 000 (rapid acceleration/ deceleration)	
Atmosphere	Room temperature	
Pulley load (N)	1 617	
Bearing load (N)	2 332	
Current (A)	0.5	–
Stopping conditions	Vibration 10 times initial level	

Table 6 Rolling life test results for energized state[14)]

	Life (h)	Spalling area
Deep groove ball bearings (steel balls)	19.6	ball
Deep groove ball bearings (ceramic balls)	>200	None

4. Introduction of high-performance tapered roller bearings

Fig. 14 shows the structure of a tapered roller bearing. Compared to ball bearings, tapered roller bearings can support higher radial and axial loads, but also generate more torque. **NTN** has developed a tapered roller bearing that achieves both low torque (low temperature rise) and long operating life by optimizing the geometry of the rolling surfaces and the inner ring large end rib face. [16)]

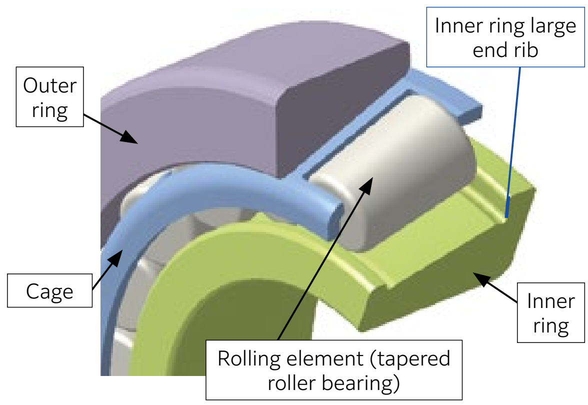


Fig. 14 Structure of tapered roller bearing[15)]

4.1 Low Temperature Rise and Low Torque Tapered Roller Bearing

The lubricating oil used in e-Axles is becoming lower in viscosity and volume in order to achieve higher efficiency in automobiles. When standard tapered roller bearings are used under these conditions, it becomes difficult for an oil film to form in the sliding contact area of the bearing rib, increasing the risk of rapid temperature rise. Our newly developed Low

Temperature Rise and Low Torque Tapered Roller Bearing improves anti-galling and reduces torque by making the design changes described in (1) to (4) below **(Figs. 15** and **16)**.

Fig. 15 Exterior of Low Temperature Rise and Low Torque Tapered Roller Bearing[16)]

(1) Compact size and low torque enabled by tapered roller and reduced pitch diameter
(2) Reduced clearance between cage inner ring and inner ring cone front face rib outer diameter reduces torque caused by agitation of lubricating oil
(3) Recessed shape added to large diameter end of cage pocket improves lubricity
(4) Optimal shape of tapered roller end face and inner ring large end rib face improves lubricity

A rotary torque test was carried out under the conditions shown in **Table 8** to compare performance between a conventional tapered roller bearing[11)] and the Low Temperature Rise and Low Torque Tapered Roller Bearing shown in **Table 7**. The test results are shown in **Fig. 17**. The Low Temperature Rise and Low Torque Tapered Roller Bearing achieved a significant torque reduction of 66 % compared to the conventional design.

Temperature rise characteristics were evaluated for the two types of bearings shown in **Table 7** under the conditions shown in **Table 9**. In this test, to simulate an oil starved environment in the e-Axle, the bearings were operated after only an extremely small amount of lubricating oil was applied to the bearing surface. The bearings were tested until the outer ring temperature reached 100 °C. The test results are shown in **Fig. 18**. The time to reach 100 °C for the Low Temperature Rise and Low Torque Tapered Roller Bearing was approximately 10 times longer when compared to the standard tapered roller bearing.

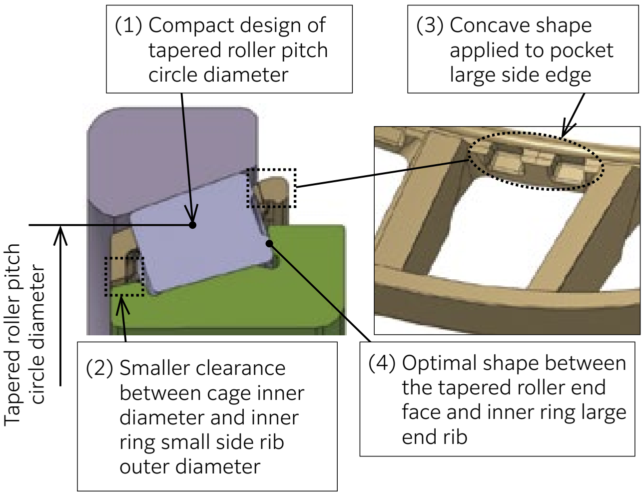


Fig. 16 Structure of "Low Temperature Rise and Low Torque Tapered Roller Bearing"[16)]

Table 7 Test bearing[16)]

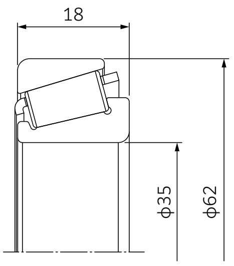
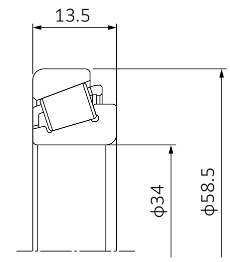
	Standard tapered roller bearing 32007X	Low Temperature Rise and Low Torque Tapered Roller Bearing
Scale drawing of bearing cross-section		
Size	ϕ35×ϕ62×18	ϕ34×ϕ58.5×13.5
Dynamic load rating	46 000 N	28 500 N
Cage	Standard steel plate cage	New shape resin cage

Table 8 Test condition[16)]

Axial load	3 000 N
Rotational speed	5 000 min^{-1}
Lubrication conditions	Oil bath ATF (50 °C)

Table 9 Test condition[16)]

Lubricating oil conditions	ATF (25 °C)
Inner ring large end rib plane contact stress	Approx. 200 MPa
Inner ring large end rib plane sliding velocity	Approx. 2.5 m/s

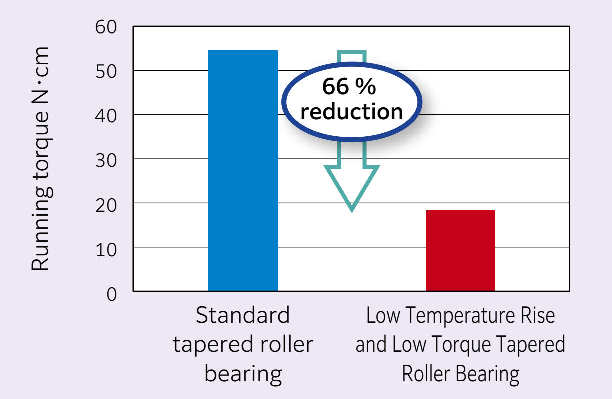


Fig. 17 Tapered roller bearing running torque test results[16)]

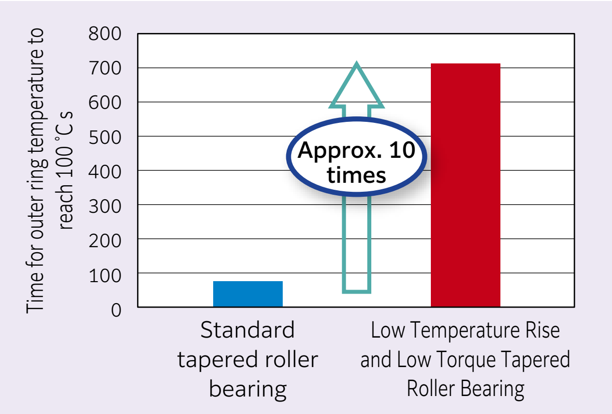


Fig. 18 Tapered roller bearing temperature rise evaluation test results[16)]

4.2 Long operating life tapered roller bearings

Here we introduce ULTAGE Tapered Roller Bearings,[15)] which feature an optimized internal bearing design to achieve high load capacity and high-speed rotational performance **(Fig. 19)**.

Fig. 19 ULTAGE Tapered Roller Bearing[15)]

ULTAGE Tapered Roller Bearings use optimized tapered roller surface geometry to maximize bearing operating life. (This technique, which involves reducing the diameter of tapered rollers toward the end in micrometer increments, is known as "crowning.") Roller crowning allows for uniform contact stress between the rolling elements and the raceways when an unbalanced load is applied. This design technology has enabled ULTAGE Tapered Roller Bearings to achieve a dynamic load rating which is 1.3x higher than conventional product and a rated life which is 2.5x higher.[*2] The geometry of the contact area on the inner ring large end rib surface was also optimized to improve the allowable rotational speed by approximately 10 %[*3].

*2: Comparison with tapered roller bearings to which the basic dynamic load rating is applied according to Japanese Industrial Standards B 1518:2013.

*3: Comparison with tapered roller bearings in **NTN** Corporation Ball and Roller Bearings Catalog (CAT.No.2203/J 20.08.199 NI/NI)

Fig. 20 compares the contact stress distribution of ULTAGE Tapered Roller Bearings and a conventional tapered roller bearing design.[11)] The ULTAGE Tapered Roller Bearings do not have excessive stress (edge stress) at the edge of the contact area due to the optimized crowning geometry.

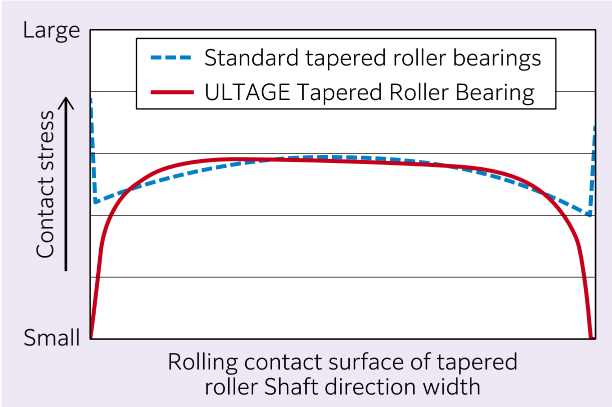


Fig. 20 Contact stress distribution on the raceway surface of a tapered roller bearing[15)]

Service life tests were conducted under the high misalignment (0.002 rad) conditions **(Table 10)** assumed for e-Axle. **Fig. 21** shows the test results. The ULTAGE Tapered Roller Bearings achieves a long operating life approximately 16 times longer than that of standard tapered roller bearings due to the uniformity of the contact stress distribution.

Table 10 Test condition[15)]

Test bearing size	$\phi23\times\phi55\times20$
Bearing material heat treatment	Standard bearing steel heat treatment
Test load	Basic dynamic load rating of 26 % (JIS B 1518:2013)
Misalignment	0.002 rad
Rotational speed	4 000 min^{-1}
Lubricating oil	ISO VG100 gear oil equivalent
JIS basic rating life	73 hours

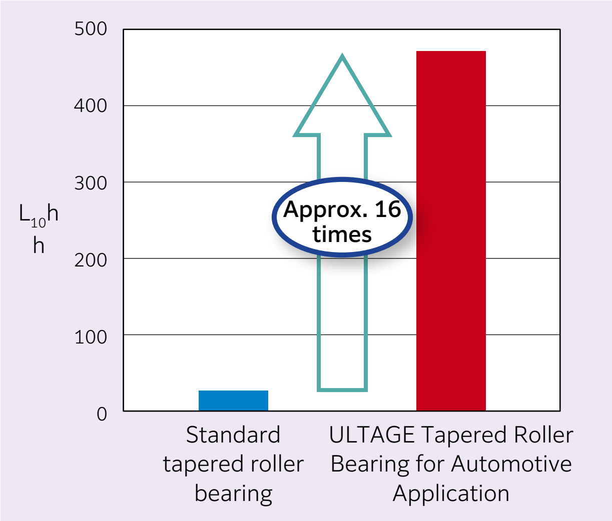


Fig. 21 Clean oil life test results for tapered roller bearings under high misalignment conditions[15)]

5. Conclusion

As the shift to electric vehicles (EVs) continues as part of the pursuit of carbon neutrality, the functions required of bearings are becoming more diverse. In this article, **NTN** introduced rolling bearings for electric drives that can meet the technical requirements of e-Axles. Looking towards the future, **NTN** will continue to develop technologies that anticipate the evolving needs of the automotive market.

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