Development of Grease-lubricated High-speed Bearing

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High-speed bearing rotation is required to make electric vehicle drive motors more efficient, smaller, and lighter. We have developed a resin cage with a novel shape that offers excellent centrifugal force resistance and lubrication performance, and that dramatically improved the high-speed performance of grease-lubricated bearings, achieving a $d_m n$ value of 1.85 million.

Key Words: *grease-lubricated, high-speed, bearing, cage, electric vehicle*

1. Introduction

In response to the worldwide issue of global warming, efforts to realize carbon neutrality and a decarbonized society are being made in various countries, while electrification is accelerating in the automobile industry. As automobile manufacturers aim to extend the cruising range of electric vehicles while improving power consumption, shortening charging times, and improving vehicle mountability, demands for drive motors to be more efficient, smaller, and lighter are increasing. Moreover, efforts are being made to compensate for decreases in output caused by smaller motors by increasing rotation speeds. For this reason, bearings that support motor shafts are also being required to provide support for high-speed rotation[1).

Deep groove ball bearings are normally used to support motor shafts and are lubricated with oil or grease. Although JTEKT has developed oil-lubricated ball bearings for high-speed rotation[2) capable of achieving 2 million $d_\mathrm{m}n$[*1], grease lubrication cannot be expected to achieve the same cooling effects of oil lubrication, resulting in grease-lubricated ball bearings seizing at approximately 1.2 million $d_\mathrm{m}n$. However, because grease lubrication eliminates the need for oil in the rotor, in turn eliminating stirring resistance during rotation, it provides the advantage of making motors highly efficient.

In this paper, we introduce the results of our successful development performed on a new product featuring excellent high-speed performance that solves the problem of bearing seizure caused by the high-speed rotation that occurs with grease lubrication. During this development, we actively used MBD[*2] to shorten the development period[3).

*1 "$d_\mathrm{m}n$" is an indicator that expresses bearing high-speed performance using the equation "ball pitch circle diameter (mm) × rotation speed (min^{-1})."

*2 MBD (Model Based Development): A highly efficient development method that significantly shortens development periods and improves product quality by creating a model for the development target and using simulation technology based on that model.

2. Issues Created by High-speed Rotation

As shown in **Fig. 1**, deep groove ball bearings consist of an inner ring, an outer ring, balls, and a cage. When grease-lubricated, seals and shields are installed on both sides of the bearing. Bearings that support the motor shaft are used for inner ring rotation, during which the balls rotate while revolving between the inner and outer rings, with the cage rotating at the revolution speed of the balls.

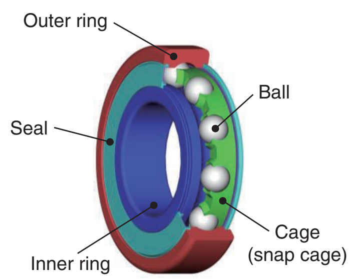


Fig. 1 Deep groove ball bearing (grease-lubricated)

There are generally two types of cages: metal and resin cages. As shown in **Table 1**, resin cages are lightweight and have self-lubricating properties, making them suitable for high-speed rotation applications. Furthermore, because injection molding is used to manufacture resin cages, a great deal of flexibility is provided in terms of shape, enabling various design concepts to be incorporated.

Table 1 Comparison of cage materials

Cage Material / Shape	Weight	Seizure resistance	Shape flexibility	Heat resistance
Resin 	○ Light	○ Self-lubricating properties	○ High (injection-molded)	Requires the use of heat-resistant materials
Metal 	× Heavy	× No self-lubricating properties	× Low (press-formed)	○ High

○ : Capable of high-speed rotation
× : Not capable of high-speed rotation

Snap cages are normally used as the resin cages for deep groove ball bearings. When the rotation speed of the motor increases to 20 000 min^{-1} and 30 000 min^{-1}, the acting centrifugal force increases accordingly. In response to this, the snap cage deforms to enable the tips of the pocket openings to open on their outside diameter, as shown in **Fig. 2**.

This causes interference with the outer ring and seals to occur, as well as ball jamming (a phenomenon in which the internal diameter of the pocket cage is pressed against the balls) (**Fig. 3** and **4**). Cage wear occurs as a result, generating powder that mixes with the grease and accelerates its deterioration. Another issue created by high-speed rotation is uneven grease distribution caused by centrifugal force, which results in the insufficient supply of grease to the contact surfaces between the raceways and balls or balls and cage. Bearings that are poorly lubricated due to reasons such as insufficient or deteriorated grease will eventually seize (**Fig. 5**).

Although high-rigidity materials and cages equipped with significantly wider ring portions for increased rigidity (hereinafter, “high-rigidity snap cages”) are used to suppress cage deformation due to centrifugal force, not only do these methods not solve the issue of insufficient grease supply, but they also result in increased cost. We, therefore, studied a cage with excellent grease lubrication at high-speed by devising a shape that does not require the use of expensive high-rigidity materials.

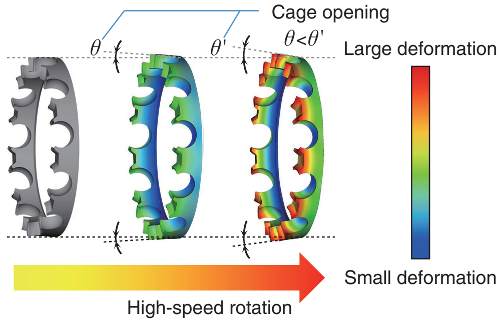


Fig. 2 Deformation of snap cage due to centrifugal force (by CAE analysis)

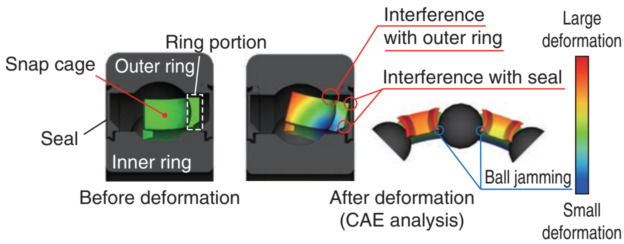


Fig. 3 Interference between snap cage and other parts due to deformation (by CAE analysis)

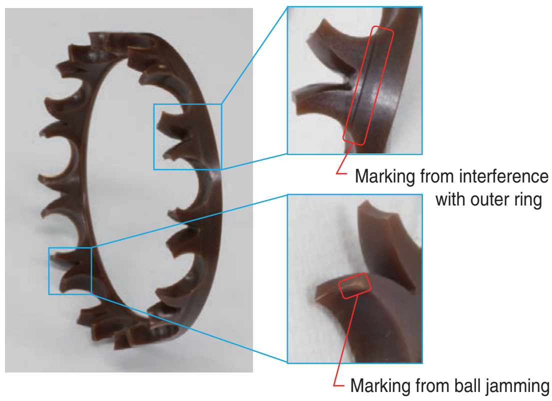


Fig. 4 Resin snap cage after high-speed test

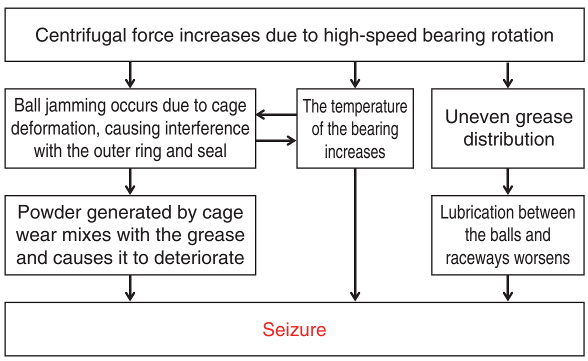


Fig. 5 Seizure generation mechanism due to high-speed rotation of bearing

3. Features of the Developed Product

In anticipation of the high-speed rotation required of future motors, we conducted our development by assuming that a bearing with an internal diameter of ϕ40mm would rotate at 25 000 min^{-1}, and therefore set a high-speed target of more than 1.5 million $d_m n$. To achieve this target, we devised a new cage shape that is less affected by centrifugal force and which improves lubricating ability (**Fig. 6**).

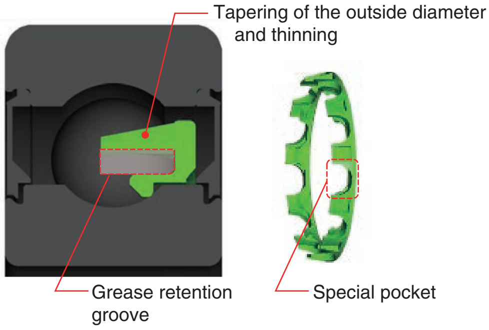


Fig. 6 Development cage

・A special pocket shape that suppresses ball jamming

Because snap cages have spherical pockets, it is impossible to avoid ball jamming due to deformation caused by centrifugal force. For this reason, the pockets were provided with a special shape that combines a semi-cylindrical shape and a flat surface in order to prevent the balls from being held by the pockets. The balls instead come into contact with the flat surfaces of the cage, preventing ball jamming due to deformation caused by centrifugal force. Claws that make contact with the inner ring raceway were also provided to position the cage in the axial direction.

・An ultra-lightweight design that suppresses deformation caused by centrifugal force (by tapering the outside diameter and thinning)

Major deformation caused by centrifugal force will result in interference with the outer ring and seal. Possible methods of suppressing the effects of centrifugal force include strengthening the rigidity of the ring portion and reducing the weight of parts other than the ring portion. Although the rigidity of ring portion can be strengthened by increasing wall thickness, the resulting increases in width would prevent the cage from fitting inside the bearing. We, therefore, made an effort to reduce the weight of parts other than the ring portion (by tapering the outside diameter and thinning), and succeeded in achieving a weight that is approximately 40% lighter than that of snap cages.

・Grease retention groove for improved lubricating ability

Uneven grease distribution during high-speed rotation worsens the lubricating ability between the balls and raceways, resulting in seizure. To improve the supply of grease to the balls and raceways, grooves for retaining the grease are provided near the balls. Supplying grease to the rotating balls via these grooves enables good lubrication to be maintained between the balls and raceways.

To confirm the effectiveness of the development cage, we used CAE analysis to verify the amount of deformation at the tip of the pockets caused by centrifugal force (**Fig. 7**). By doing so, we were able to verify that deformation had been reduced by approximately 70% compared to that of snap cages.

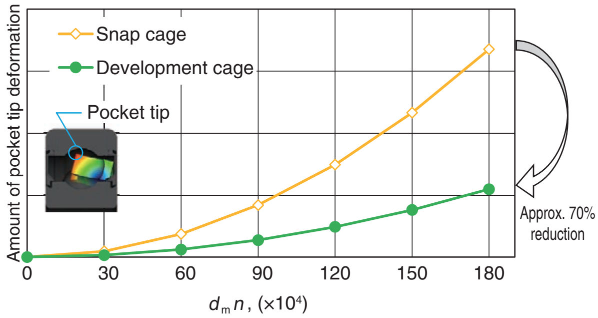


Fig. 7 Amount of deformation of cage due to centrifugal force

4. Developed Product Performance

4. 1 High-speed Performance

To confirm the high-speed performance of the development cage, we conducted tests in which the rotation speed was gradually accelerated. During these tests, we would measure the temperature of the bearing outer ring to confirm temperature stability and would repeatedly increase the rotation speed to look for abnormal temperature increases, which occur when the temperature of the bearing continues to rise due to increases in rotation speed and eventually lead to seizure. Test conditions are shown in **Table 2**, while test results are shown in **Fig. 8**. While abnormal temperature increases were observed in the high-rigidity snap cage (snap cage with a wider ring portion for increased rigidity) when 1.2 million $d_m n$ is exceeded, no such abnormal temperature increases were seen in the

Table 2 High-speed test conditions

Bearing size	ϕ40mm ID × ϕ80mm OD × 18mm width
Rotation speed	Gradual acceleration to 1.85 million $d_m n$

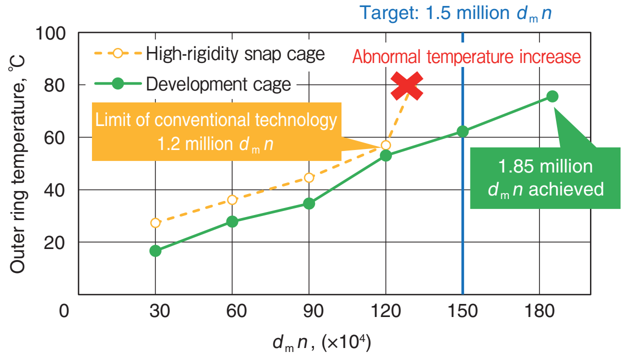


Fig. 8 High-speed test results

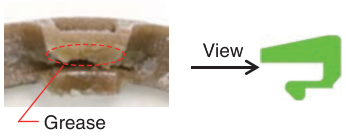


Fig. 9 Development cage after test

development cage even at 1.85 million $d_m n$. Moreover, when observing the cage following testing, we found no abnormal interference with other parts and observed that grease had been retained within the grooves of the cage (**Fig. 9**). Supplying the retained grease to the balls enables good lubrication to be maintained even during high-speed rotation, and we feel we have greatly exceeded our targets for high-speed performance.

4. 2 Individual Cage Fatigue Strength

When a bearing rotates under a combined load, the contact angle with the raceways changes during one revolution of the balls. This causes the orbital distance of each ball to fluctuate slightly, increasing the contact force between the ball and cage. The effects of repeated contact force may cause the cage to suffer fatigue failure. To confirm the fatigue strength of the development cage, tests were conducted in which contact force was repeatedly added in a manner that simulated actual equipment (**Fig. 10**). The test conditions are shown in **Table 3**.

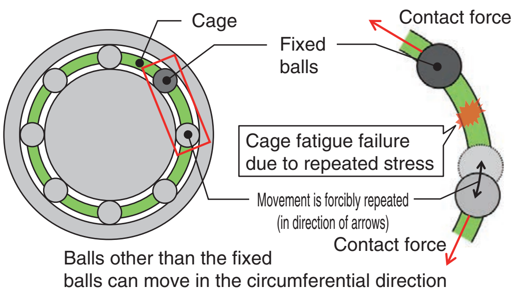


Fig. 10 Method of adding contact force to cage

Table 3 Fatigue strength test conditions for cage

No. of load-bearing cycles	1.5 × 10^7 cycles
Applied load	40 N

As a test load, a contact force (contact force generated at a high-speed rotation of 1.85 million $d_m n$) calculated by dynamic simulation*3 (**Fig. 11**) was applied. Test results showed that the cage did not fracture, indicating that our target was achieved. Moreover, because no whitening or damage occurred, we could confirm that the development cage possesses sufficient fatigue strength.

*3 Bearing analysis program developed in-house by JTEKT[4)]

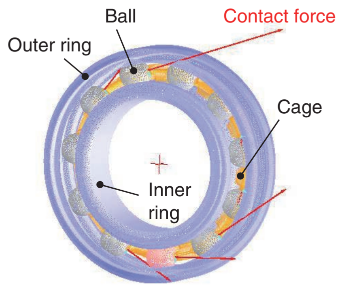


Fig. 11 Contact force analysis example

4. 3 Durability Assessment

We conducted the following durability tests to confirm the durability of the development cage.

- High-speed endurance tests: Simulates conditions during continuous high-speed operation
- Urgent acceleration and deceleration endurance test: Simulates conditions during rapid starting and stopping

During these tests, the bearing was heated using an external heater, after which a temperature load was applied in order to simultaneously confirm its heat resistance. The test conditions are shown in **Table 4**. The results of both tests showed that the target time and number of cycles had been achieved, and that the cage had suffered no damage (**Table 5**). We were therefore able to confirm that the development cage possesses sufficient durability.

Table 4 Endurance test conditions

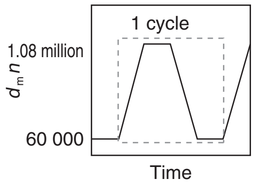
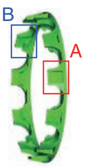
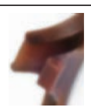
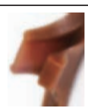
Test name	High-speed endurance test	Urgent acceleration and deceleration endurance test
Bearing size	ϕ40mm ID × ϕ80mm OD × 18mm width	
d_mn	1.5 million	60 000 ⇔ 1.08 million 
Outer ring temperature	140℃	80℃
Target test time / Target no. of cycles	20 h	150 000 cycles

Table 5 Endurance test results

Test name		High-speed endurance test	Urgent acceleration and deceleration endurance test
Cage after test 	A	 No interference with outer ring	 No interference with outer ring
	B	 No damage to pocket or claw	 No damage to pocket or claw
Test result		Target time achieved	Target time achieved

4. 4 Conclusion

Shown in **Table 6** are the test results for a bearing that employs a development cage with a new shape that improves grease lubrication and high-speed performance. During high-speed performance tests, the rotation speed was gradually accelerated, during which 1.85 million d_mn was achieved, far exceeding our target. Meanwhile, during fatigue strength tests for the cage, a contact force calculated via dynamic simulation was added to the cage itself, enabling us to confirm that sufficient fatigue strength was maintained due to the fact that the target number of load-bearing cycles was achieved. During endurance tests, a high-speed endurance test and urgent acceleration and deceleration endurance test were conducted. Because both tests showed that targets had been achieved, we were able to confirm that endurance was sufficient.

Table 6 List of test results

Test item		Test result	
High-speed performance test		○	1.85 million d_mn achieved
Fatigue strength test for cage		○	Target no. of load-bearing cycles achieved
Endurance test	High-speed endurance test	○	Target time achieved
	Urgent acceleration and deceleration endurance test	○	Target no. of cycles achieved

5. Conclusion

During the development of a bearing cage for grease lubrication and high-speed rotation as outlined in this paper, we were able to confirm that the high-speed performance of the cage is 1.5 times that of conventional high-rigidity snap cages, and that it achieved a high-speed rotation of 1.85 million d_mn, making it one of the top cages in the world. A series[5] of high-speed rotation bearings featuring the developed cage and designed for use in the motors of EV drive units has already been released. The bearings in this series support high-speed rotation for more efficient, smaller, and lighter motors, while contributing to improved power consumption and longer cruising ranges. As part of our efforts to contribute the automotive electrification, we will continue our development of products with high levels of added value.

References

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