

Development of a Plastic Cage for High-temperature and High-speed Bearings

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Among those bearings used under high-speed applications, some are actually used at operating temperatures up to 200°C.

Under such severe operating conditions, polyetheretherketone, which is an extremely high heat-resistant thermoplastic, is sometimes used. But its cost is very high.

By our study a suitable crown type cage for high-temperature/high-speed application has been designed using Polyamidimide with good creep performance and polyphenylenesulfide with good chemical resistance. These materials form an original composition that makes use of each material's superior characteristics.

As a result, a lower cost cage has been developed which can be used in high-speed use conditions in an environment up to 200°C.

Key Words: plastic cage, plastic alloy, polyphenylenesulfide, polyamidimide, creep performance

1. Introduction

For rolling bearing cages, resin materials have been widely used because they have better self-lubricity than metals. Generally, crown type cages made from thermoplastic resins capable of injection molding, are often used because they allow high productivity and ease of assembly.

However, resin cages have a problem with decreasing stiffness under high temperature and large dimensional change due to creep (hereinafter referred to as "creep") under high-speed centrifugal force.

Some bearings for automotive engine accessories operate at temperatures as high as 200°C. For these bearing cages, materials are required to have a good balance between heat resistance and cost. However, the more heat resistant the resin is, the higher its cost is, as shown in Fig. 1. In such stringent operating conditions as described above, polyetheretherketone (hereinafter called "PEEK"), is used. It has the highest heat resistance among available thermoplastic resins, though its cost is very high.

We have recently developed a new lower cost resin cage, which can withstand a 200°C operating environment, while having similar creep resistance to PEEK in high-speed operation.

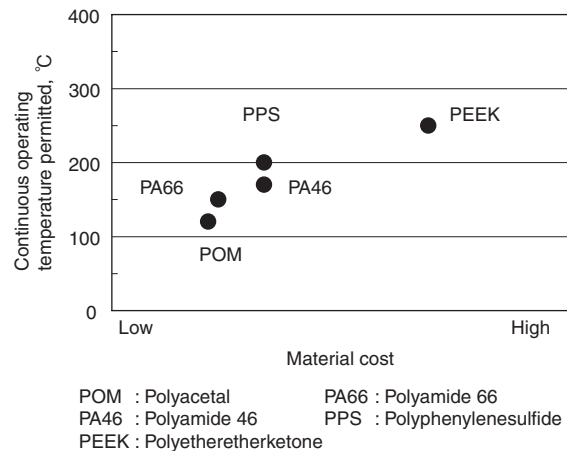


Fig. 1 Relationship between continuous use temperature and cost

2. Development of Material

2.1 Selection of Matrix Resin

Bearing cage material is required to have chemical resistance (or compatibility with greases, oils, and cleaning solvents) as well as creep resistance. As far as the chemical resistance is concerned, crystalline resins excel, whereas non-crystalline resins are good for creep resistance at high temperatures. Therefore, we have tried a material design that alloys these different types of resins to make the best use of each respective resin's features.

Polyphenylenesulfide (hereinafter called "PPS") which has high moldability was selected for a crystalline resin.

Polyamidimide (hereinafter called "PAI") with excellent friction-wear properties, was chosen for a non-crystalline resin. Various compositions of these resins were tested to find the optimum composition.

2. 2 Optimization of Material Composition

In order to identify the effect of the composition of PAI and PPS, as well as the effect of reinforcement fibers on required wear resistance and creep resistance, a series of frictional wear tests was conducted¹⁾. **Table 1** shows various material compositions of the tested samples. Ratios for PAI and PPS of 3:5 and 3:7, were selected on the basis of capability of injection molding and definite improvement in creep resistance compared to PPS only. For reinforcement, glass fiber (hereinafter called "GF") and carbon fiber (hereinafter called "CF") were used for the test.

Table 1 Material compositions

| Sample No. | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 |
|--------------|----------|----------|----------|----------|----------|----------|----------|
| Matrix resin | PAI | PAI+PPS | PPS | PAI+PPS | PPS | PPS | PPS |
| PAI : PPS | 1 : 0 | 3 : 5 | 3 : 7 | 0 : 1 | 3 : 5 | 3 : 7 | 0 : 1 |
| GF (mass %) | 30 | 30 | 30 | 30 | - | - | - |
| CF (mass %) | - | - | - | - | 30 | 30 | 30 |

2. 2. 1 Frictional Wear Test

The test was conducted on a disc-on-ring frictional wear tester under conditions shown in **Table 2**. Dimension change due to wear (hereinafter called "wear dimension change") and creep dimension change were determined by the following equations:

$$\text{Wear dimension change} = \frac{\Delta w}{S \cdot \rho}$$

$$\text{Creep dimension change} = \Delta t - \frac{\Delta w}{S \cdot \rho}$$

where,

- ρ : Density of resin material
- S : Area of wear surface of test piece
- Δw : Weight change of test piece
- Δt : Height change of test piece

Table 2 Test conditions

| Items | Condition | | |
|---------------------|--|-------------------|---------------------|
| Test equipment | Disc-on-ring test equipment | | |
| Test piece | Ring test piece (20 dia. mm * 25.6 dia. mm * 15mm) | | |
| Counter material | Disc (40mm * 40mm * 3mm) | Material | S45C |
| | | Surface roughness | 0.4 μmRa |
| Sliding speed | 0.5 m/s | | |
| Sliding distance | 6 000 m | | |
| Contact pressure | 3 MPa | | |
| Ambient temperature | Room temperature | | |
| Lubricant | Grease (fluoro grease) | | |
| Measurement | Weight change of ring test piece Height change of ring test piece | | |

Test results are shown in **Figs. 2** and **3**. In **Fig. 2**, wear dimension change was generally low irrespective of content of PAI and PPS. The difference between the matrix resins gave little influence on the results. This seems to be due to grease lubrication used in the test set up. GF reinforced materials show creep resistance decreases with the increase in PPS content.

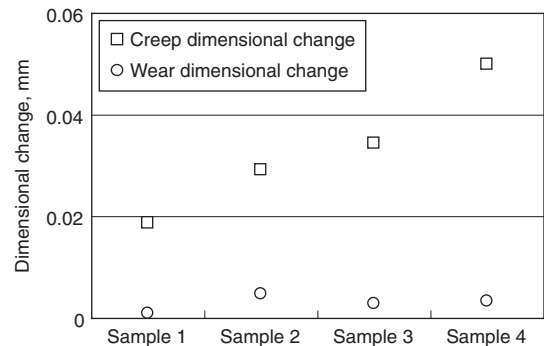


Fig. 2 Result of wear test 1

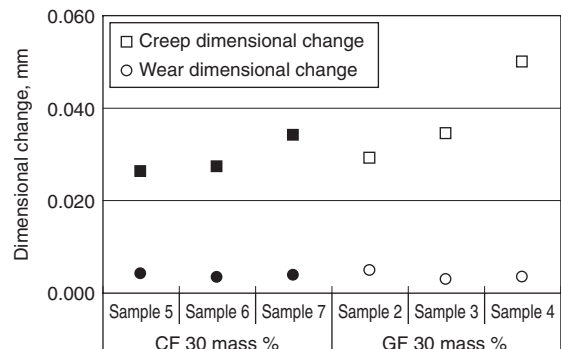


Fig. 3 Result of wear test 2

Figure 3 shows that CF reinforcement is more effective than GF reinforcement in reducing creep dimensional change. Like CF reinforcement, increased content of PPS worsened creep dimension change, though the difference between matrix resins is smaller than GF reinforcement.

This difference is caused by the difference in specific gravity between CF and GF. Because the same content of reinforcement in terms of mass was used (30 mass %), the lighter reinforcement, i.e. CF, occupied the larger volume, leaving less volume for resin material. This was observed in the appearance of the wear surface after the test, as shown in **Fig. 4**. Since creep takes place in the resin-rich part, CF reinforced samples seem to show less difference in creep among resin materials.

On the other hand, the wear dimension change for all samples was generally low, and this was considered to be the effect of grease lubrication as in case of the GF reinforcement study.

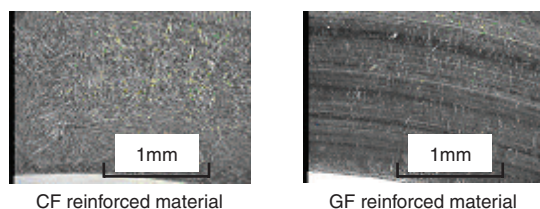


Fig. 4 Appearance of wear surface

2.3 Creep Resistance Test on Cages

From the results of the friction wear test, it was confirmed that CF reinforcement is more effective than GF reinforcement for improving the creep resistance of resin cages. However, taking account of the fact that creep resistance is influenced by fiber orientation, another series of creep resistance tests were conducted under simulated centrifugal force, on cage samples with the same fiber orientation as generated in actual production molding.

In this test, a sample cage was exposed to a temperature of 200°C for a preset time with a steel ball placed on the opening side of the cage tongues, simulating the centrifugal force. Change of dimension of the cage tongue was measured after exposure and evaluated as the creep dimensional change (**Table 3, Fig. 5**).

From the test results shown in **Fig. 6**, PAI + PPS + CF (samples 5 and 6) showed smaller creep dimensional change than PEEK + GF. It was verified that the proposed compound was effective in improving creep resistance in the actual cage form. Between the 3:5 and 3:7 compounds of PAI and PPS with CF reinforcement, the creep resistance performance was about the same, but it was decided to perform further development with 3:7 compounds with better moldability.

Table 3 Test conditions

| Items | Condition | |
|------------------|------------------|---------------|
| Test environment | 200°C atmosphere | |
| Test duration | 160 hours | |
| Steel ball | Size | 40 dia. |
| | Weight | Approx. 260 g |

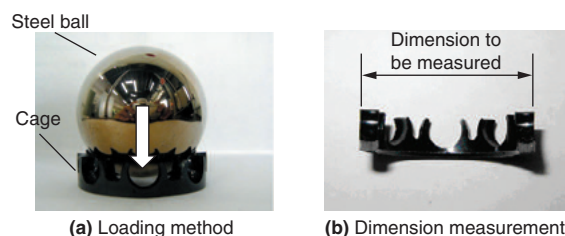


Fig. 5 Creep test method for cage

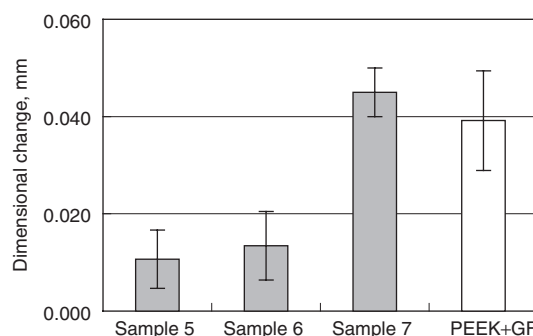


Fig. 6 Results of cage creep test

3. Cage Design

3.1 Problem

In high-temperature/high-speed operation, the cage tongue portion of the opening side of the cage may expand toward its outer diameter (hereinafter called "OD") due to the centrifugal force acting on the cage. In a condition where the centrifugal force acts continuously with the creep dimensional change, this expansion of OD increases as time passes. Should the extent of this problem be very high, it can cause biased abrasion on the bore or OD of the pockets (in which the balls are retained) (**Fig. 7 (a), (b)**), or fracture or cracks on the cage tongue (**Fig. 7 (c), (d)**) can occur in more serious cases.

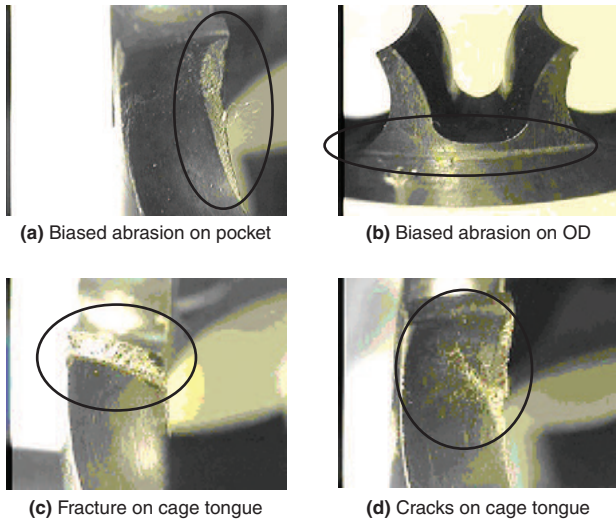


Fig. 7 Damage areas of the cage

3. 2 Discussion

To counter these problems, the following changes to the cage design have been proposed and studied. Also the effectiveness of these changes in high-temperature/high-speed operation was confirmed by FEM analysis.

- 1) Inclination of the cage tongues on the opening side toward the bore.
- 2) Optimization of PCD and pocket diameter.

The design change 1) is intended to restrict biased abrasion due to contact between balls and cage pockets, even in cases where the opening side cage tongues are forced to open by the centrifugal force in operation.

Optimization of PCD and pocket diameter 2) is aimed at minimizing the freedom of the cage to prevent the cage from getting in contact with the inner or outer ring.

3. 2. 1 Inclination of Opening Side Cage Tongue toward Bore

Under operating conditions of 200°C and 18 000 min⁻¹, deformation of the cage due to centrifugal force and thermal expansion was determined and relative position of the ball and cage was confirmed.

Figure 8 shows the outline of a FEM model prepared, and the parameters for analysis are summarized in Table 4. A 1/14 model was employed, taking symmetry into account, to confirm the deformation of the cage under the high temperature (200°C) and centrifugal force imposed.

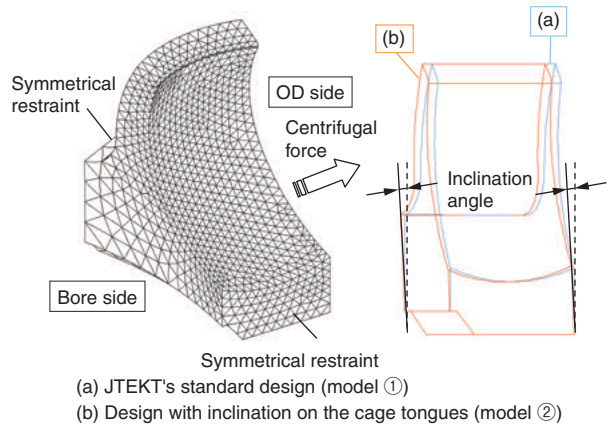


Fig. 8 FEM model

Table 4 Analysis conditions

| Items | Condition |
|-----------------------|--|
| Type of analysis | Material: Geometrically non-linear |
| Temperature condition | Heating from room temperature to 200°C |
| Loading condition | Centrifugal force around rotating axis |

The analysis was performed on two models; one is JTEKT's standard design without inclination (hereinafter called model ①); the other was the cage design with inclination of the cage tongue toward the bore (hereinafter called model ②). Figure 9 shows the results of analysis detailing relative position of the cage and balls before and after transformation (initial ball position was coincident with the PCD). In the model ① at high temperature/high speed operation, clearance between the balls and cage is reduced on the bore side, so that they are more likely to come in contact, whereas in model ②, ball-cage clearance is sufficient to make contact unlikely between the ball and cage. As the inclination angle of the cage is geometrically limited, further analysis was conducted to determine the limit of the inclination used for final cage design.

In Fig. 10, the distance between the cage and outer ring at high temperature/high speed operation (by FEM analysis) is compared between the model ① and the model ②. From this comparison, the model ② has 0.66mm larger clearance between the balls and the outer ring land than the model ① which is JTEKT's standard design. It is thus confirmed that the inclination of the cage tongue effectively prevents biased abrasion due to the contact of cage with the outer ring land.

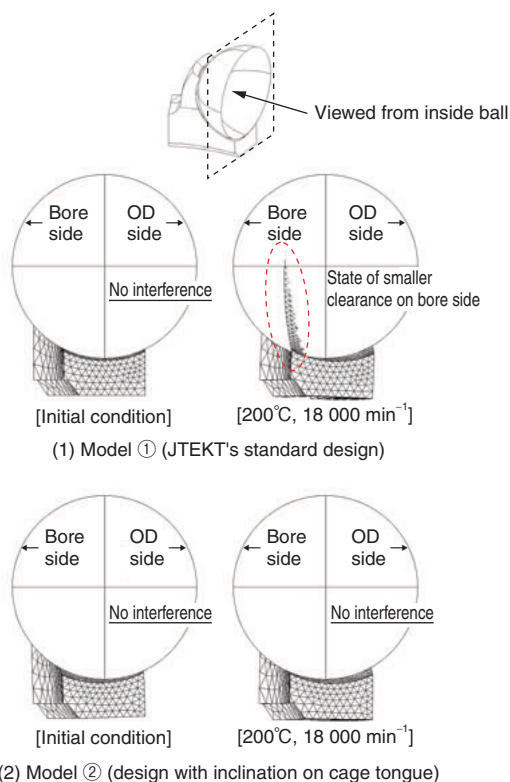


Fig. 9 Position of cage and ball before and after transformation

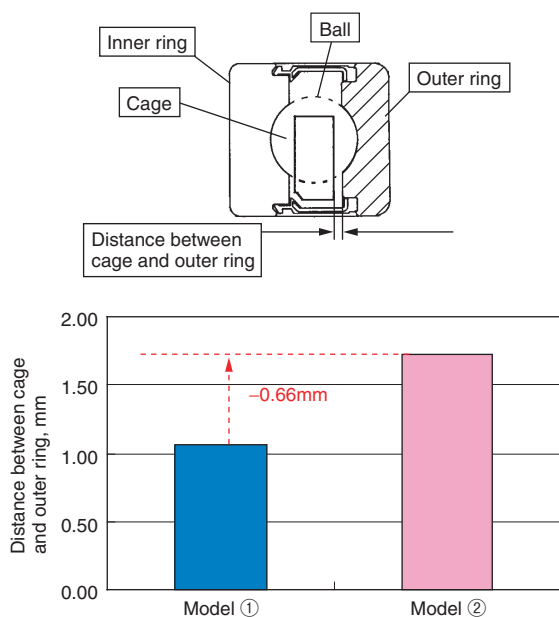


Fig. 10 Distance between cage and outer ring during high-speed rotation at high temperature

3. 2. 2 Optimization of PCD and Pocket Diameter

Free movement of the cage in the bearing was analyzed for a cage with optimized PCD and pocket diameter.

The following two models were used:

- 1) Cage design with inclination on the cage tongue (model ②).
- 2) Cage design with inclination on the cage tongue and optimized PCD and pocket diameter (hereinafter called model ③).

Analysis procedures were as follows:

- 1) Analysis of cage deformation under centrifugal force and thermal expansion by a 1/14 model (Fig. 9).
- 2) Reproduction of full model (1/1) from the 1/14 model after deformation.
- 3) Setting rigid surface steel balls equally spaced into the pocket of model 2) between the inner and outer rings.
- 4) After fixing the outer and inner rings and applying gravity, evaluating movements of the balls and the cage.

Resultant contour diagrams of movement are shown in Fig. 11. The model ② with inclination only (Fig. 11 (a)) showed marked movement of both balls and cages due to their dead weight, while the clearance between the cage and inner and outer rings are smaller.

On the other hand, in the model ③ with optimized PCD and pocket diameter (Fig. 11 (b)), both the balls and cage moved due to dead weight smaller than the model ② with the inclination only, and hence it kept larger clearance between the cage and outer ring. It was found, therefore, that the model ③ is less liable than model ②, to have cage contact with inner and outer rings.

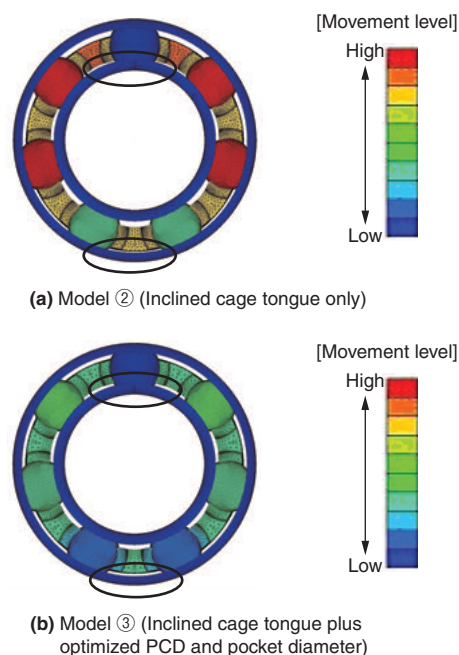


Fig. 11 Position of ball and cage in gravitational field

3. 2. 3 Ease of Assembly

Figure 12 shows a contour diagram of the maximum main stress resulting from a FEM analysis simulating the cage insertion process in a bearing assembly (model ③ cage design). The stress value identified in this analysis was smaller than the permissible stress of the developed material. It was confirmed, therefore, that the change of cage design has negligible effect on assembly of the cage.

From the above analysis, it was established that providing inclination on the cage tongues toward the bore can restrict biased abrasion due to contact between the ball and pocket surface. Also, it was established that optimizing the PCD and pocket diameter is effective in restraining the cage from contacting with the inner or outer ring land.

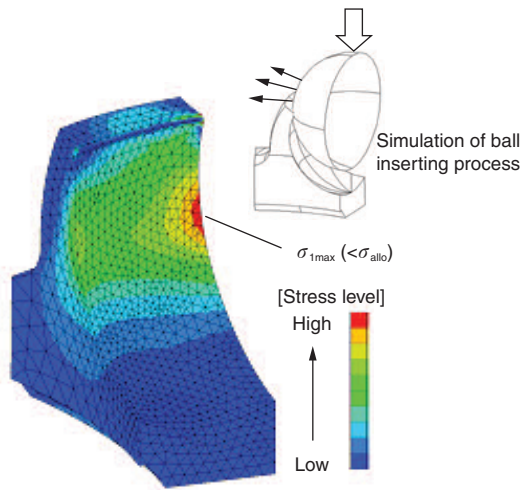


Fig. 12 FEM analysis of maximum main stress

4. Bearing Performance Tests

Taking into consideration the aforementioned analysis results, samples of resin cages incorporating the inclined cage tongues and optimized PCD and pocket diameter (hereinafter called developed cage design) were prepared. They were tested to verify assembly ease and the effect of restraining contact between balls and cage, as well as contact between the inner/outer ring and the cage.

4. 1 Assembly Test

In the assembly test, balls were first arranged between the inner and outer rings at the same pitch as the cage pockets. Then, the cage was inserted over the balls on a press while measuring the maximum load required to insert the cage. After the test, the cage was inspected for damage (cracks or whitening). The test was conducted in room temperature, and pressing speed was 10mm/min.

As Fig. 13 shows, the maximum load required to insert the cage was about the same between the developed and JTEKT's standard cages. Whitening, cracks or other damages were not observed in either of these cages.

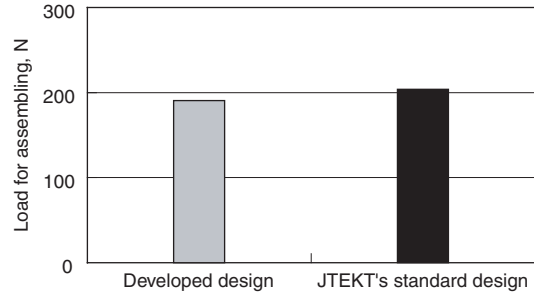


Fig. 13 Results of assembly test

4. 2 High-Temperature/High-Speed Durability Test

High-temperature/high-speed durability testing was conducted on test equipment as shown in Fig. 14. Test bearings were radially loaded by coil springs, while the inner ring was rotated by a driving motor through V-belt. The outer ring OD temperature was controlled at 200°C.

The test conditions are summarized in Table 5 and the test results are shown in Table 6. The test bearing incorporating the developed cage design satisfied the specified test time of 1 000 hours.

Figure 15 shows cage appearance after the durability test. The plastic cage after the test did not show any crack, fracture or any other damage, verifying that the developed cage is useful in a 200°C environment.

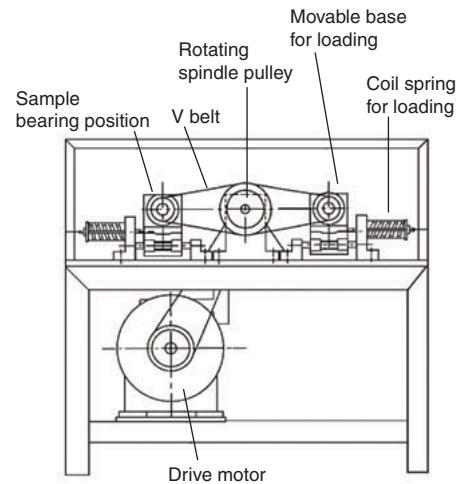


Fig. 14 Test equipment

Table 5 Test conditions

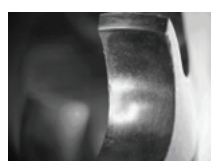
| Items | | Condition | |
|-------------------|-----------------------------------|----------------------------|------|
| Test bearing | Type | Deep groove ball bearing | |
| | Boundary dimensions, mm | ID: 17 dia. OD: 52 dia. | |
| | Cage | PAI+PPS+CF | |
| Test conditions | Load, kN | Radial | 1.32 |
| | | Axial | 0 |
| | Rotating speed, min ⁻¹ | 18 000 | |
| | Lubrication | Fluoro grease | |
| | Temperature, °C | 200 (Outer ring OD) | |
| | Test duration, hrs | 1 000 | |
| Number of samples | | 2 | |

Table 6 Result of durability test

| Sample No. | 500 | 1 000 [h] | |
|------------|-----|-----------|------------------------|
| 1 | | | 1 000 hours, suspended |
| 2 | | | 1 000 hours, suspended |



(a) General view



(b) Enlarged view of pocket

Fig. 15 Appearance of cage after durability test

5. Conclusion

By use of an alloy of two matrix resins, polyamidimide (PAI) and polyphenylenesulfide (PPS), and carbon fiber (CF) for reinforcement, a new plastic material for bearing cage has been developed. It has equivalent performance to glass fiber reinforced polyetheretherketone (PEEK), and can be practically used under such severe conditions as 200°C at a high speed.

By taking account of characteristics of the developed material and designing optimized crown type cages, ball bearing cages applicable for high-temperature/high-speed conditions can be provided.

Reference

- 1) S. Nagai, H. Arai: Proceedings of Tribology Conference (in Tottori 2004-11) 55.



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