Effects of segment-structured DLC film on the fretting wear of railway axle journal bearings

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Abstract
Fretting wear is surface damage caused by repeated slight relative slips between two contact surfaces. In railway applications, fretting wear can occur between the inner ring and the backing ring of an axle journal tapered roller bearing. The authors supposed that the fretting wear of the backing ring can be prevented by means of hard-film coatings if hard films can follow the deformation of the backing ring. A segment-structured diamond-like carbon (S-DLC) film has been proposed to solve this problem. In this work, the authors investigated the effect of S-DLC film on the fretting wear through rotation tests of full-scale railway axle bearings with the backing ring side face coated with S-DLC film or conventional continuous diamond-like carbon (C-DLC) film. As the result, the S-DLC film coated backing ring demonstrated less wear compared to the C-DLC film coated backing ring. In addition, the iron content of the grease in the bearing with the S-DLC film coated backing ring was lower than that of the grease in the bearing with the C-DLC film coated backing ring. It is conceivable that the relative sliding motion in the radial direction between them may be restrained by the latticed pattern of the S-DLC film being pressed into the inner ring large side face. It is concluded that the S-DLC film is effective in suppressing the fretting wear generated on the contact surfaces between them of the axle bearings.

Keywords : Bearing, Fretting, Wear, Diamond-like carbon, Segment-structure

1. Introduction

Axle journal tapered roller bearings in railway applications (axle bearings) carry both radial loads acted by vehicle weight, and axial loads generated when railway vehicles pass through curves and turnouts. Two inner rings and a backing ring of the axle bearing are fitted onto the axle journal as shown in Fig. 1. One of the inner rings contacts with the backing ring. When the axle bearings subjected to radial loads rotate, the axle journal bends due to rotary bending. Under these conditions, fretting (Shima and Jibiki, 2008) occurs by relative motion between the inner ring and the backing ring. If metallic wear particles caused by the fretting penetrate inside the bearing, the bearing contact surfaces may wear and/or the lubricant may deteriorate. Furthermore, there is a possibility of causing irregularity in the axial mounted position of the axle bearings due to the fretting wear. For measures to prevent the fretting of the axle bearings, techniques to insert either a rubber-attached spacer (Oka, 2013) or an O-ring (Takano and Asai, 2004) between the inner ring and the backing ring were proposed. Although these means can prevent the fretting wear particles from being mixed into the lubricant, they are not able to prevent the generation of fretting itself essentially. In addition, the inserts increase the number of parts of the axle bearing and may cause operational errors during assembly work. To the authors’ knowledge, there is no study on the way to take measures to prevent the fretting wear of the axle bearings without increasing the number of parts. It is, therefore, necessary to develop the prevention measures of the fretting itself.
In our previous studies, the authors investigated the effects of the contact pressure between the inner ring and the backing ring on the fretting in order to elucidate the mechanism of the fretting generation; through a reproduction test of fretting using a full-scale axle bearing in order to understand the fretting wear behavior between them. As the result, the authors found that (1) the fretting wear between them becomes more remarkable on the outer side of their contact surfaces in the radial direction, (2) the contact pressure between them distributes all over the contact surface, especially on its outer side in the radial direction, and (3) the fretting wear area of the backing ring is approximately coincident with the area where the amplitude of the contact pressure is large (Okamura et al., 2016).

Based on the above results, the authors attempted coating the backing ring side face with hard substances that do not wear though it receives a high contact pressure to prevent the fretting wear of the axle bearings without increasing the number of parts. Specifically, three types of hard films (titanium nitride (TiN), chromium nitride (CrN) and diamond-like carbon (DLC)) were selected, which are generally widely applied to prevent wear of cutting tools, sliding parts, and metal molds. Results indicate that hard films with a lower friction coefficient and higher hardness are effective in suppressing the fretting wear of the backing ring. In particular, the CrN film and the DLC film remained partly on the backing ring side face after the test, though some cracks and decohesion occurred in both films because the films were not able to follow the deformation of the backing ring due to the rotary bending of the axle (Okamura et al., 2018b). Accordingly, there is a possibility that cracks and decohesion in films can be suppressed if the films can follow the deformation of the backing ring, so that the fretting wear of the backing ring can be prevented. To solve these problems, a segment-structured DLC (S-DLC) film has been proposed as DLC film capable of following the deformation of the base material (Aoki and Ohtake, 2004, Takashima et al., 2009). The S-DLC film is able to follow the deformation of the base material by reducing the strain generated on the DLC film even if a large strain is applied to the film. As an application example of S-DLC film, it is already known that the S-DLC coated shim which is inserted between two plates can prevent the fretting wear.

The aim of this paper is to investigate a preventing effect of S-DLC film on the fretting wear of the backing ring side face through some rotation tests using full-scale axle bearings.

2. Test procedures

2.1 Test bearing

The bearings used for rotation tests were double row tapered roller bearings lubricated with lithium soap grease, which are widely used as axle bearings of railway vehicles. The axle bearing is composed of an outer ring with two raceways, two sets of non-separable inner ring, cage and roller assemblies, a backing ring, etc. The dimensions of the test bearing are outer diameter of 220 mm, inner diameter of 120 mm and width of 155 mm. The inner rings and the backing ring are attached to the axle with interference fits, i.e., the contact surfaces between the inboard inner ring and the backing ring are not allowed to perform a relative motion in the circumferential direction. The backing ring was
manufactured from normalized medium-carbon steel JIS S45C, and the inner ring was manufactured from carburized steel equivalent to JIS SNCM 420 steel. Their contact surfaces were coated with a phosphate film with a thickness of approximately 5 μm.

2.2 Diamond-like carbon film

It is generally known that the formation of hard films such as ceramics on the surface of metallic materials improves their sliding properties, wear resistance, seizure resistance, corrosion resistance, etc. In this work, in order to prevent the above-mentioned fretting wear occurring between the inner ring and the backing ring, DLC film was applied to the backing ring side faces contacting the inner ring in consideration of the workability of the surface treatments and the productivity of the axle bearings. DLC film was formed by plasma chemical vapor deposition (CVD) method where the substrate temperature during the deposition was below 523 K. The type of DLC films used was hydrogen-containing DLC (a-C:H, hydrogenated amorphous carbon). In order to improve the adhesion of DLC film to the side surface (Lee et al., 1996), the phosphate coating on the surface was removed and the surface was smoothed by grinding; furthermore, a silicon (Si) interlayer was provided between DLC film and the base material. The addition of Si is effective to reduce the internal stress of the DLC film so that the DLC film exhibits higher bonding strength to the base material. The arithmetic average roughness, Ra on the backing ring side face decreased from 0.78 μm to 0.13 μm by grinding.

Figure 2 shows a sectional structure in the radial direction of the backing ring side face covered with the DLC film, which was observed using a scanning electron microscope (SEM, acceleration voltage 15 kV) after etching in 5 vol% nital (5 % nitric acid + 95 % methanol). Figure 2 also shows a typical example of DLC film formed along the shape of the base material, and a dual-phase structure of ferrite and pearlite in the base material. The mean thickness of the DLC film was 1.7 μm.

Table 1 shows the properties of the DLC film used. The indentation hardness (HIT) was measured with a test force at which the indentation depth became about one-tenth of the thickness of the DLC film using a nanoindentation tester in accordance with ISO14577–1 (International Organization for Standardization, 2015).

<table>
<thead>
<tr>
<th>Properties of the DLC films used.</th>
<th></th>
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<tbody>
<tr>
<td>Indentation hardness, GPa</td>
<td>16.5</td>
</tr>
<tr>
<td>Film thickness, μm</td>
<td>1.7</td>
</tr>
<tr>
<td>Friction coefficient *</td>
<td>0.17–0.21</td>
</tr>
</tbody>
</table>

* Against JIS SUJ2 bearing steel under dry friction

The S-DLC films were formed by depositing DLC after a tungsten mesh wire had been placed on a backing ring side face. The tungsten wire used had a mesh of 50 μm in diameter and the grid interval was 250 μm. Figure 3 shows an example of an optical microscope image of the S-DLC film. It is apparent that segment structure with lattices approximately 200 μm interval on a side is formed.
Figures 4 and 5 show the appearance and the profile curve of the backing ring side face coated with S-DLC film and conventional continuous DLC (C-DLC) film, respectively. The profile curves were measured from the inner diameter side to the outer diameter side using a stylus type surface roughness measuring instrument. The arithmetic average roughness, $Ra$ on the backing ring side face coated with S-DLC film was 0.33 $\mu$m, which is larger than the one after grinding. This is due to the surface asperity formed S-DLC film. On the other hand, the $Ra$ on the backing ring side face coated with C-DLC film was 0.12 $\mu$m, which was approximately equal to the arithmetic average roughness after grinding.

Fig. 4 The backing ring side face coated with S-DLC film before the test. The arithmetic average roughness, $Ra$ is 0.33 $\mu$m.

Fig. 5 The backing ring side face coated with C-DLC film before the test. The arithmetic average roughness, $Ra$ is 0.12 $\mu$m.

2.3 Bearing rotation test condition

A rotation test was conducted with the performance test rig for axle journal bearings owned by Railway Technical Research Institute. The test rig used is illustrated in Fig. 6. This rig allows us to perform a rotation test on two full-scale axle bearings at the same time under a constant or a fluctuating load condition.
The test condition was set based on the performance tests for axle journal rolling bearings specified in Japan Association of Rolling Stock Industries Standard, JRIS J 0455, and the radial and axial loads applied to the test bearings were set based on the rating life for axle journal rolling bearings specified in JRIS J 0453. Table 2 and Fig. 7 show the test conditions and the operation cycle of the rotation test, respectively. The test was performed while alternately repeating clockwise rotation and counterclockwise rotation until the total number of revolutions of the inner ring reached $231.5 \times 10^6$ revolutions corresponding to the cumulative distance of 600,000 km. The surface temperatures of the outer rings during the rotation tests were within the range of the predetermined regulation value (ambient temperature +70 K or less) and were about 55 K higher than the ambient temperature at the maximum.

![Fig. 6 Schematic illustration of the performance test rig for axle journal bearings.](image)

**Table 2** Test conditions.

<table>
<thead>
<tr>
<th>Test load</th>
<th>Radial</th>
<th>87.4 kN</th>
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<tbody>
<tr>
<td></td>
<td>Axial</td>
<td>±14.7 kN (intermittent 5 s)</td>
</tr>
<tr>
<td>Axle maximum rotational speed</td>
<td>1 930 min$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Clockwise and counterclockwise</td>
<td></td>
</tr>
<tr>
<td>Cooling method</td>
<td>Air-cooling</td>
<td></td>
</tr>
<tr>
<td>Air speed</td>
<td>Approximately 10 m/s</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 7 Operation cycle based on JRIS J 0455 consisting of a clockwise and a counterclockwise rotations.](image)
3. Results
3.1 Segment-structured DLC film
3.1.1 Visual images and wear depth distributions of contact surfaces

Figures 8 and 9 show the appearance and the wear depth distribution of the backing ring side face and the inboard inner ring large side face after the rotation test using the backing ring side face coated with S-DLC film, respectively. The wear depth distribution was measured in the circumferential direction using a two-dimensional laser displacement sensor. As shown in Figs. 8a and 9a, wear is observed on both contact surfaces, and the color of the grease attached to the inner ring changes to reddish brown. Fretting wear particles are generally known to be reddish-brown iron (III) oxide ($\alpha$-Fe$_2$O$_3$) (Waterhouse, 1972). If fretting occurs between the contact surfaces of the backing ring and the inner ring, and fretting wear particles generated mix with grease, the color of the grease becomes reddish brown. It follows from the above that the wear of the backing ring side face coated with S-DLC film was fretting wear. As shown in Figs. 8b and 9b, the fretting wear of the backing ring side face occurs all over the contact surface and relatively severe fretting wear occurs in its outermost circumference in particular, whereas the fretting wear of the inner ring occurs all over the contact surface with the backing ring.

![Fig. 8](image_url)

(a) Appearance
(b) Wear depth distribution

Fig. 8. The backing ring side face coated with S-DLC film after the rotation test. The fretting wear of the backing ring side face occurs all over the contact surface and relatively severe fretting wear occurs in its outermost circumference in particular.

![Fig. 9](image_url)

(a) Appearance
(b) Wear depth distribution

Fig. 9. The inboard inner ring large side face after the rotation test. The fretting wear of the inner ring occurs all over the contact surface with the S-DLC coated backing ring.

3.1.2 Surface images and profile curves

Surface images and profile curve measurements were carried out for the area having severe fretting wear (red marks) and the area having relatively slight fretting wear (yellow marks), respectively, in Figs. 8 and 9. During the
bearing rotation test, the backing ring and the inner ring were in contact with each other at the coordinate phase of the circumference direction.

Figures 10 and 11 show the microscope images and their profile curves of the backing ring side face and the inner ring large side face of the severe fretting wear area, respectively. The fretting wear of the backing ring side face shown in Fig. 10 was remarkable on the outside diameter and the maximum wear depth was approximately 0.22 mm from the surface. Although no segment structure is observed on the surface of the inner diameter side, wear is little. On the other hand, the fretting wear of the inner ring large side face shown in Fig. 11 can be seen at the contact surface with the backing ring from the center to the outer diameter in the radial direction, and the maximum wear depth was approximately 0.10 mm from the surface. The wear area of the backing ring side face corresponds with that of the inner ring side face. In addition, the fretting wear of the backing ring is more remarkable than that of the inner ring.

Figures 12 and 13 show the microscope images and their profile curves of the backing ring side face and the inner ring large side face of the relatively slight fretting wear area, respectively. The segment structure can be recognized on the contact surface of the backing ring shown in Fig. 12a. The profile curves in Fig. 12b and 12c exhibit little fretting wear on the S-DLC coated surface and the clear rugged pattern formed by S-DLC film. Figure 13 also indicates that there is little fretting wear on the inner ring large side face. Furthermore, it can be seen that the segment structures on the backing ring side face are transferred to the inner ring large side face by contact with the backing ring. As shown in Fig. 13c, the enlarged profile curve of the transferred area indicates that the inner ring large side face is plastically deformed by the latticed pattern of the S-DLC film being pressed.
In order to examine whether the S-DLC film coated on the backing ring side face remains after the rotation test, the contact surface of the backing ring was analyzed with an energy dispersive X-ray analyzer (EDX) attached to the SEM (acceleration voltage of 15 kV). The elements to be analyzed were iron (Fe), and Si in the interlayer between the DLC film and the base material.

Figure 14 presents the SEM/EDX images of the areas of (1) and (2) in Fig. 10a where the fretting wear was relatively slight area after the rotation test. The segment structure can be recognized on the contact surface of the backing ring.

Fig. 12 The microscope image and its profile curve of the S-DLC coated backing ring side face of the relatively slight fretting wear area after the rotation test. The segment structure can be recognized on the contact surface of the backing ring.

Fig. 13 The microscope image and its profile curve of the inner ring large side face of the relatively slight fretting wear area after the rotation test. The segment structures on the backing ring side face are transferred to the inner ring large side face by contact with the backing ring.

3.1.3 Surface analysis by an energy dispersive X-ray

In order to examine whether the S-DLC film coated on the backing ring side face remains after the rotation test, the contact surface of the backing ring was analyzed with an energy dispersive X-ray analyzer (EDX) attached to the SEM (acceleration voltage of 15 kV). The elements to be analyzed were iron (Fe), and Si in the interlayer between the DLC film and the base material.

Figure 14 presents the SEM/EDX images of the areas of (1) and (2) in Fig. 10a where the fretting wear was relatively slight area after the rotation test. The segment structure can be recognized on the contact surface of the backing ring.
significant. It can be confirmed that the entire S-DLC film disappeared because Si was not detected at any area. On the other hand, it can be seen that the S-DLC film has remained on the inner diameter side as it was not in contact with the inner ring, as shown in Fig. 14a.

Figure 15 presents the SEM/EDX images of the areas of (1) to (3) in Fig. 12a where the fretting wear was relatively slight. At the area of (1) in Fig. 12a where the segment structures were observed on the surface, the S-DLC film completely remains. In addition, it can be confirmed that the S-DLC film remains slightly at the area of (2) in Fig. 12a where the contact surface showed a brown color in the surface observation. On the other hand, the S-DLC film does not remain at the area of (3) in Fig. 12a where the contact surface showed a slightly black color. As can be seen from the above, the S-DLC film has been removed from the contact surface in the radial direction towards the outer side.

3.2 Continuous DLC film

3.2.1 Visual images and wear depth distributions of contact surfaces

Figures 16 and 17 show the appearance and the wear depth distribution of the backing ring side face and the inboard inner ring large side face after the rotation test using the backing ring side face coated with C-DLC film, respectively. As shown in Figs. 16a and 17a, wear is observed on both contact surfaces, and the color of the grease attached to the inner ring changes to reddish brown. It follows from the above that the wear of the backing ring side face coated with C-DLC film was fretting wear. The fretting wear of the backing ring side face occurs all over the
contact surface with the inner ring from the center to the outer diameter in the radial direction. As previously described (Okamura et al., 2016), this is because the backing ring goes up the tapered portion of the axle journal and is expanded radially, when the axle bearing is fitted onto the axle journal. The fretting wear of the inner ring occurs all over the contact surface with the backing ring. From these results, it can be seen that the fretting wear of the C-DLC film is more remarkable than that of the S-DLC film.

![Image](a) Appearance (b) Wear depth distribution

**Fig. 16** The backing ring side face coated with C-DLC film after the rotation test. The fretting wear of the backing ring side face occurs all over the contact surface with the inner ring from the center to the outer diameter in the radial direction.

![Image](a) Appearance (b) Wear depth distribution

**Fig. 17** The inboard inner ring large side face after the rotation test. The fretting wear of the inner ring occurs all over the contact surface with the backing ring.

### 3.2.2 Surface images and profile curves

Surface images and profile curve measurements were carried out for the area having severe fretting wear in Figs. 16 and 17. During the bearing rotation test, the backing ring and the inner ring were in contact with each other at the coordinate phase of the circumference direction.

Figures 18 and 19 show the microscope images and their profile curves of the backing ring side face and the inner ring large side face after the rotation test. The fretting wear of the backing ring side face shown in Fig. 18 becomes larger in proximity to its outer circumference and the maximum wear depth was approximately 0.18 mm from the surface. On the other hand, the fretting wear of the inner ring large side face shown in Fig. 19 can be seen at the contact surface with the backing ring from the center to the outer diameter in the radial direction, and the maximum wear depth was approximately 0.10 mm from the surface. The wear area of the backing ring side face corresponds with that of the inner ring side face. Moreover, the fretting wear of the backing ring is more remarkable than that of the inner ring. The fact that the fretting wear generated remarkably at the radially outer contact surface is the same tendency as the previous works (Okamura et al., 2016, 2018a, 2018b).
3.2.3 Surface analysis by an energy dispersive X-ray

In the same method as described in 3.1.3, in order to examine whether the C-DLC film coated on the backing ring side face remains after the rotation test, the contact surface of the backing ring was analyzed with the EDX. The elements to be analyzed were Fe and Si.

Figure 20 presents the SEM/EDX images of the areas of (1) to (3) in Fig. 18a. It can be confirmed that the entire C-DLC film disappeared because Si was not detected at any worn area in contrast to the S-DLC film coating. On the other hand, it can be seen that the C-DLC film has remained on the inner diameter side as it was not in contact with the inner ring, as shown in Fig. 20a.

3.3 Iron content in grease

In order to investigate the effect of S-DLC film on the fretting wear prevention, the grease to be analyzed was sampled from the tested bearings and the iron content in the grease was determined by a scanning X-ray fluorescent spectrometer. The grease sampling locations were the inside of the cage bars and the roller large end faces of the inboard inner ring of the tested bearings. Table 3 summarizes the results of the iron content of the grease sampled. Table 3 includes the results of a bearing installed the backing ring without DLC film coating (Okamura et al., 2018a).

Comparing the iron content by the grease sampling location, in all tested bearings the iron content of the grease at the roller large end faces, which is close to the contact surface between the inner ring and the backing ring, is higher than that of the grease inside the cage bars. In addition, comparing the iron content of the grease at the roller large end faces between S-DLC film and C-DLC film, the iron content of the grease in the bearing with the S-DLC film coated
backing ring is lower than that of the grease in the bearing with the C-DLC film coated backing ring, especially the roller large end faces.

4. Discussion

From the results of the bearing rotation tests, the fretting wear was observed on the backing ring side faces coated with both S-DLC and C-DLC films. Nonetheless, the S-DLC film coated on the backing ring side face has still remained in the EDX images, and the wear depth distributions and the profile curves of the contact surfaces have shown that the S-DLC film coated backing ring demonstrated less wear compared to the C-DLC film coated backing ring. In addition, the iron content of the grease in the bearing with the S-DLC film coated backing ring was lower than that of the grease in the bearing with the C-DLC film coated backing ring. These results indicate that the fretting wear of the backing ring can be reduced due to S-DLC film coating. The reason why the fretting wear of the S-DLC film coated backing ring was reduced is discussed below.

When an axle bearing is fitted onto an axle journal, the backing ring goes up the tapered portion of the axle journal and is expanded radially, so that the backing ring side face deforms (Okamura et al., 2016). Furthermore, some cracks
and decohesion can occur in C-DLC film because the film coated on the backing ring side face is not able to follow the iteration deformation of the backing ring due to the rotary bending of the axle (Okamura et al., 2018b). On the other hand, it is considered that the S-DLC film can follow the deformation of the backing ring side face because DLC film with segment structured can relax stress generated within the film even when the backing ring is distorted (Aoki and Ohtake, 2004). As the result, the S-DLC film remained on the backing ring side face after the rotation test. Additionally, as mentioned in 3.1.2, the fretting wear between the inner ring and the backing ring was slight at the area where the segment structures were transferred to the inner ring large side face. This is presumably because the relative sliding motion in the radial direction between the inner ring and the backing ring can be restrained by the latticed pattern of the S-DLC film being pressed into the inner ring large side face. Consequently, such behavior on the contact surface between them can suppress the fretting wear. It is concluded from the above mentioned that the S-DLC film is effective in suppressing the fretting wear generated on the contact surfaces between them of the axle bearings.

Now the authors have reported in our previous paper (Okamura et al., 2016) that the fretting wear generated remarkably at the radially outer contact surface being subjected to higher contact pressure between them. As mentioned in 3.1.3, it was observed that S-DLC film was removed from the contact surface in the radial direction towards the outer side (see Figs. 12 and 15). Since the actual contact pressure distribution between them is not uniform, more uniform one is desirable to reduce the fretting wear. A method to realize more uniform one is described below. The rigidity of the backing ring can be reduced by providing some grooves on its oil seal sliding surface. Thereby, the high contact pressure between them can be moderated, resulting in making the contact pressure distribution uniform (Okamura et al., 2018a). Therefore, it is expected that the fretting wear can be further suppressed by combining the backing ring that can make the pressure distribution more uniform and that coated with S-DLC film.

5. Conclusions

In order to investigate the preventing effect of segment-structured diamond-like carbon (S-DLC) film on the fretting wear which occurs between the inner ring and the backing ring of the axle bearings, the authors conducted the rotation tests using full-scale axle bearings coated with S-DLC film or conventional continuous diamond-like carbon (C-DLC) film. The main remarks obtained are shown below.

(1) The fretting wear has been observed on the backing ring side faces coated with both S-DLC and C-DLC films. Nonetheless, the S-DLC film coated on the backing ring side face has still remained in the EDX images, and the wear depth distributions and the profile curves of the contact surfaces have shown that the S-DLC film coated backing ring demonstrated lower wear compared to the C-DLC film coated backing ring.

(2) The iron content of the grease in the bearing with the S-DLC film coated backing ring was lower than that of the grease in the bearing with the C-DLC film coated backing ring.

(3) The fretting wear between the inner ring and the backing ring was slight at the area where the segment structures were transferred to the inner ring large side face. This is presumably because the relative sliding motion in the radial direction between them may be restrained by the latticed pattern of the S-DLC film being pressed into the inner ring large side face.

It has been concluded from the above mentioned that the S-DLC film is effective in suppressing the fretting wear generated on the contact surfaces between them of the axle bearings.

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