INFLUENCES OF ADDITIVES ON THE WEAR PROTECTION OF PVD-COATED AND ESTER LUBRICATED ROLLER THRUST BEARINGS

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KEYWORDS
PVD-coating, roller bearing, mixed friction conditions, additives, ester lubrication

ABSTRACT
Mixed friction cannot always be avoided in rolling bearings. It is therefore necessary to protect the bearings against wear. Nowadays, extreme-pressure- and anti-wear-additives fulfill this function. As these additives are harmful to the environment it was systematically examined to what extent PVD-coatings are able to take over their function. The effectiveness of the coatings was tested in the FE8 lubricant roller bearing test rig on the basis of cylindrical roller thrust bearings. With the help of this world wide established test rig the roller bearings are tested on boundary friction conditions ($\kappa \ll 1$).

INTRODUCTION
If roller bearings run under unfavorable or mixed lubrication conditions, extreme-pressure- and anti-wear-additives in the lubricant protect the bearings against wear in order to reach long working life. A separating tribo-layer is produced between the friction partners rollers and washers. Disadvantages of the additives are partially environmental toxicology and the cause of pollution. [1]

To replace these toxic additives and to realize an environmental friendly ester lubrication of the roller bearings, the ability of PVD-coatings (physical vapor deposition) is investigated to take over the additive's function. The final goal is a PVD-coated roller bearing system, which is lubricated by an environmental friendly ester without additives. This research is done in one subproject as a part of the German Collaborative Research Centre “SFB 442” [1].

The aim of the presented tests is to show that PVD-coatings are able to protect roller bearings from wear in unfavorable or mixed lubrication conditions. The test results state also that additives are not active on ZrC$_x$-coated roller bearing surfaces. Therefore the additive’s function on coated and un-coated bearing surfaces is investigated and their ability to protect un-coated rollers which run on coated bearing washers.

EXPERIMENTAL METHODS
The tests are made on the example of axial cylindrical roller thrust bearings. These bearings (bearing type: 81212) consist of a housing washer and a shaft washer, which are honed as surface finishing. 15 rollers, mounted in a brass cage, are forced on a circular running track. Consequently, pure rolling motion only takes place in the centre of the cylindrical roller thrust bearings. Their drill motion causes a rising slippage (up to 14%) towards their ends. If a fully separating lubricating film is missing, sliding wear arises in the areas of positive and negative slippage. In the centre of the rolling contact the wear is small because of the low glide ratio. In the area of large wear, the height of rolling elements and washers is reduced. Simultaneously the deformation and the pressure decrease. In addition to the pressure, the rate of wear is reduced in these areas. As a consequence, the wear process in the cylindrical roller thrust bearings has a degressive character over the time. Apart from the adhesive and abrasive wear, fatigue damages can arise early in coated bearings, too. From the moment in time when the first fatigue damage occurs the wear process becomes progressive. These complex cinematically motion and
wear conditions in axial cylindrical roller thrust bearings make them to ideal tribological test elements.

The tests are performed on the FE8 test rig, which is illustrated in Fig. 1. Two cylindrical roller thrust bearings can be examined at the same time. The load is applied by two plate springs and can be varied by different distance plates. The friction torque is measured by a rope wheel, the rope of which is connected to a load cell [2]. The test conditions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1 FE8 test system and test conditions</th>
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<tbody>
<tr>
<td>Test system:</td>
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<tr>
<td>Test rig</td>
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<tr>
<td>Test sample</td>
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<tr>
<td>Bearing type</td>
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<tr>
<td>Lubrication:</td>
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<tr>
<td>Method of lubrication</td>
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<tr>
<td>Lubricant</td>
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<tr>
<td>Circulating oil volume</td>
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<tr>
<td>Volume flow</td>
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<tr>
<td>Degree of filtration</td>
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<tr>
<td>Test conditions:</td>
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<tr>
<td>Rotational speed</td>
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<tr>
<td>Axial load</td>
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<td>Bearing temperature</td>
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<td>Operation time</td>
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</table>

The main criterion of evaluation is the loss of mass of the rolling elements after 80 h running time. To measure this loss of mass the bearings are disassembled and the rollers and washers are weighed separately. If the additional wear of all rollers is less than 10 mg after 80 hours operation time and no fatigue damages arose, the wear protection of the coating or the lubricant can be evaluated as excellent according to the experience of the German collaborative research project “SFB 442” [1] and other research projects [3], [4]. Good wear protection is given for roller wear between 10 mg and 30 mg and average wear protection for roller wear between 30 mg and 100 mg. In case of coated elements the coating’s wear protection has failed, if its amount of wear is greater than 10 mg. It is supposed that the full coating is worn and no more able to serve an adequate wear protection. The complete classification system for bearing wear is shown in Table 3.

Table 2 Classification of wear for the FE8 roller bearing and lubricant test rig after 80 h operation time

<table>
<thead>
<tr>
<th></th>
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<tr>
<td>0 mg to 10 mg</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
</tr>
<tr>
<td>10 mg to 30 mg</td>
<td>good</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td>30 mg to 100 mg</td>
<td>average</td>
<td>average</td>
<td>poor</td>
</tr>
<tr>
<td>over 100 mg</td>
<td>poor</td>
<td>poor</td>
<td>poor</td>
</tr>
</tbody>
</table>

EXAMINED PVD-COATING, LUBRICANTS AND ADDITIVES

Table 3 shows the properties of the different elements of the tribo-system like the PVD-coating, the lubricants and the additives. All elements were developed within the German Collaborative Research Centre.

The ZrC₉-coating, which was deposited on the roller bearings, was deposited by the Material Science Institute in Aachen [5]. With its hardness of 11 GPa and an E-Modulus of 182 GPa the ZrC₉-coating was the best performing coating of various roller bearing tests. Besides its wear resistance in boundary friction conditions it showed an excellent bonding to the substrate. The coating’s structure is graded, that means the carbon content rises form the substrate surface (no carbon, just a bonding-layer of zirconium) to the top of the surface (pure carbon, no more zirconium) as displayed in Fig. 2. This coating system reduced the roller wear from the un-coated case with an amount of 1200 mg to a roller wear of 2 mg after 80 hours of testing time (as presented later and shown in Fig. 3). Physical vapour deposition (PVD) process was used, which guarantees a temperature smaller than the tempering temperature of the substrate (100Cr6). The loss of hardness is here less important than the change of accurate dimensions [6]. The thickness of the examined ZrC₉-coating is about 2 to 2.5 µm.

Three different lubricants were tested. Two additive-free mineral oils (FVA 3 reference oil, ISO VG 100 and FVA 2 reference oil, ISO VG 32) were used as lubricants in order to leave the additive’s wear protection mechanisms out of consideration. Both lubricants have also the advantage that its composition is known. Furthermore, they will be available in the same quality for a long time. The third lubricant is an additive-free synthetic ester oil (ISO VG 32). The substance is a Hydroxyisobutoxystearinsäuremethylester. It is produced by
the Institute for chemical Technology and heterogeneous catalysis [7].

**Table 3 Tested lubricants, additives and the coating**

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Type of Oil</th>
<th>Additives</th>
<th>ISO VG</th>
</tr>
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<tbody>
<tr>
<td>40.X.0.HISM.32</td>
<td>Ester Oil</td>
<td>additive-free</td>
<td>32</td>
</tr>
<tr>
<td>7.C.O.M.100</td>
<td>Mineral Oil</td>
<td>additive-free</td>
<td>100</td>
</tr>
<tr>
<td>51.X.0.M.32</td>
<td>Mineral Oil</td>
<td>additive-free</td>
<td>32</td>
</tr>
</tbody>
</table>

- **Additive** Type of Additive   Content
- Additin RC 3760     AW  0.25%
- Additin RC 2415     EP  1.50%

The new developed synthetic ester lubricant was tested in combination with or without one anti-wear-additive (Additin RC 3760) and/or one extreme-pressure-additive (Additin RC 2415) of Rhein Chemie.

**RESULTS**

In the present tests un-coated and ZrCg-coated bearings were examined. In case of ZrCg-coated bearings, just the bearing washers were coated, the rollers stayed un-coated. If the coated washers show signs of wear, the wear protection ability of the coating or maybe its bonding to the substrate 100Cr6 is insufficient. If loss of mass is indicated on the un-coated rollers, the coating’s ability to protect an un-coated counterpart is not given. Both mechanisms, the substrate protection and the counterpart protection, have to be active for a successful wear protection of a roller bearing by a PVD-coating system.

**Fig. 3. FE8 test results for different lubricants in coated and un-coated condition**

In a first test series the different lubricants from Table 3 were tested concerning their influence on the coating’s wear resistance in a roller bearing. Fig. 3 displays the results, the roller wear and the wear of the washers.

Following the wear results it can be stated that the standard additive-free mineral oil lubricant (7.C.O.M.100) with a viscosity of ISO VG 100 is not able to protect the roller bearing elements in an appropriate way. Without any additives the wear of the washers and the rollers is more than 1200 mg. If the washer surfaces are ZrCg-coated, their amount of wear decreases to 6 mg. The wear protection mechanism of the coating is enormously and nearly avoids any wear. Even the un-coated rollers, which run on the coated washer surfaces, benefit from the coating by a reduction of wear to 2 mg and excellent wear protection.

A lubricant with a lower viscosity (ISO VG 32) and the same composition (the same standard mineral oil) shows a similar behavior. Without any additive the amounts of wear are very high (washers: 802 mg and rollers: 1089 mg). By coating the bearing’s washers with ZrCg the wear could be minimized to 2 mg for washers and rollers.

In a next step the new developed synthetic ester lubricant 40.X.0.HISM.32 was tested in the FE8 test rig, also with a viscosity of ISO VG 32. Just the utilization of this ester enlarged the wear protection of the roller bearing. In comparison to the mineral oil tests the ester oil performed quite well in the test with 72 mg washer wear and 34 mg roller wear in the un-coated case. The additionally employment of the ZrCg-coating on the washers increased the wear protection of the washers to only 2 mg (excellent wear protection). Surprisingly, the enhanced wear protection behavior of the washers could not be transferred to the rollers as observed in the mineral oil tests. Their loss in mass was independent of weather the washers were coated or not. It remained with 38 mg wear in the same order as in the coated version. Just average wear protection could be testified.

In the second test series it was investigated, if the ZrCg-coating is directly able to take over the additive’s function. Therefore, the anti-wear-additive and the extreme pressure-additive in combination with the environmental friendly ester lubricant 40.X.0.HISM.32 (ISO VG 32) and/or the ZrCg-coating were examined in the FE8 test rig.

**Fig. 4. Influence of anti-wear- and extreme pressure-additive on the wear protection of the ZrCg coating for coated and un-coated bearing washers**

In Fig. 3 just the wear results of the bearing washers are displayed. Without coating and without additive the amount of wear is quite high (more than 80 mg). The ZrCg-coating on the washers or the usage of the anti-wear-additive reduce the wear enormously to average 1.75 mg and less than 1 mg. The utilization of the anti-wear-additive and the ZrCg-coating confirm their excellent wear protection even in their combination. The addition of the extreme pressure-additive pays not
out. The washer’s wear is not significantly reduced and is in the same order as the pure lubricant.

The protection of the un-coated counterpart, the rollers, is shown in Fig. 4. The coating’s reduction in wear is within ester lubrication not as large as in the mineral oil lubricated tests, whether ISO VG 100 or ISO VG 32. The wear of the rollers, which run on coated washer surfaces, is more than 20 mg (good wear protection). The anti-wear-additive inflates its wear protection on the rollers as long as no coating is present. But in combination with ZrC
\(_2\)-coated washers the anti-wear-additive does not work on the rollers. Here, the wear is in the same order as without additive. As the washers, the rollers are not affected by the extreme-pressure-additive, too.

DISCUSSION

The ZrC
\(_2\)-coating performs excellent independent from the kind of lubricant. The substrate is protected by the coating in mineral oil and synthetic ester lubrication. The difference between the tests with and without coating on the washers is almost enormously. Furthermore the wear protection of the ZrC
\(_2\)-coating is not affected in the tests by the lubricant’s viscosity. Whether the viscosity of the mineral oil is ISO VG 100 or ISO VG 32, the use of the coating reduces the washer’s wear and supplies excellent wear protection.

As long as the bearings were mineral oil lubricated the un-coated rollers profit from the coating on the washers. Their wear was reduced in the same way as that from the coated elements. By an ESMA analysis (electron beam micro range analysis) and pictures of the scanning electron microscope it could be proved, that in case of carbonaceous coatings more or less material carryover from the coating to the steel surface was developed (see Fig. 5). The steel surface showed the coating element tungsten and oxygen in the contact zone of the coated rollers to the un-coated washers (see Fig. 6). The carbon content was on the running track and beside it slightly constant. Consequently, the rise in wear protection of the un-coated rollers from the test results of Fig. 5origins not from transferred carbon from the ZrC
\(_2\)-coating. More information gave a XPS analysis (X-Ray Photoelectron Spectroscopy). This method revealed a Fe
\(_2\)O
\(_3\) layer on the surface of un-coated bearing elements, which run on coated surfaces. Similar reaction layers are produced by state-of-the-art additives and well known as life-time improvers.

This wear protection mechanism for un-coated counterparts with contact to a coating is obviously not active in ester lubrication. The coating on the washers did not affect the amount of wear of the rollers (34 mg to 38 mg, see Fig. 5). Possibly, the ester oil prohibits the formation of a wear protecting reaction layer on the rollers. Maybe this effect is due to the relatively more reactive ester oil, which might form a reaction layer on the rollers by itself. But this layer is not as resistant as the reaction layer formed by the coating and finally the bearing suffers under wear.

The wear protection of the ZrC
\(_2\)-coating is similar to that of the anti-wear-additive. Both strategies end up with nearly no wear and even in their combination. Both wear protection mechanisms do not influence the other one negatively. It is for sure that the surface protection mechanism of the coating is dominating the process as it performs directly from the beginning on the substrate. The reaction layer of the additive needs some time for development.

The extreme-pressure-additive does not perform at all. Maybe the pressure and temperature, which are necessary for its operation, are not present within the test rig conditions of Table 1. The extreme-pressure-additive does not influence the performance of the coating or the anti-wear-additive significantly.

Fig. 5. Influence of anti-wear- and extreme-pressure-additive on the wear protection mechanism of the ZrC
\(_2\)-coating for un-coated rollers

Fig. 6. Material carryover and smoothing in the bearing “WC/C / 100Cr6”

Fig. 7. ESMA analysis of the un-coated washer, which run on coated rollers (see Fig. 2). The carbon content is constant over the full measuring length, oxygen and tungsten enriched areas are along the running track.
The wear results of the un-coated counterpart, the rollers, shown in Fig. 4, reveal again that the material transfer process or the reaction layer formation by the coating is obviously not acting during ester lubrication. Here, the anti-wear-additive is more successful and forms its protection layer on the un-coated rollers independently from the kind of lubricant. But in combination with ZrC\textsubscript{g}-coated washers the anti-wear-additive loses its function. This additive reduces not the amount of wear in comparison to the test with coated washers and additive-free ester lubricant.

CONCLUSION

It was systematically examined on the basis of cylindrical roller thrust bearings to what extent PVD-coatings are able to take over the function of extreme-pressure- and anti-wear-additives. The bearings were tested under heavy-duty conditions in order to quickly distinguish their efficiency.

The presented test results give the evidence that PVD-coatings are able to protect roller bearings in serve lubricating conditions. The ZrC\textsubscript{g}-coating on the washers is acting excellent and produces a wear protecting tribo-layer on the un-coated roller surfaces. This mechanism is not working in combination with ester lubrication. Here, the need of a coating on both friction partners becomes obvious. This combination realizes an environmental compatible tribo-system.

The fact that additives reduce the bearing wear for about the same amount as the ZrC\textsubscript{g}-coating is presented in further tests. The ZrC\textsubscript{g}-coating or the anti-wear-additive shows the same results in wear protection. The anti-wear-additive does not minimize the wear of coated bearing elements. Even un-coated friction partners are no more protected by an anti-wear-additive while they run on ZrC\textsubscript{g}-coatings.

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