Influence of Operating Conditions and Additive Concentration on the Formation of Anti-wear Layers in Roller Bearings

Andreas Stratmann [1)], Gero Burghardt [1)], Georg Jacobs [1)]

[1)] Institute for Machine Elements and Machine Design, RWTH Aachen University, Germany

Summary

In the mixed and boundary friction regime, wear of rolling bearings can be influenced significantly by the combination of base oil and additive. Additives in the lubricant can form anti-wear layers on the contacting surfaces of the bearing and inhibit the direct steel-steel contact thus reducing adhesive and abrasive wear. The mechanisms of the layer formation in highly loaded machine elements are mostly unknown. To ensure a wear-free lifetime of the elements, a protective layer must be formed. This study provides a contribution to the influencing parameters on this layer formation. Tests were conducted with cylindrical roller thrust bearings. Limits of the anti-wear layer formation were identified by varying the operational parameters rotational speed, load and temperature and the additive parameters concentration and structure.

1. Introduction

Failures of rolling bearings, operated in the mixed and boundary lubrication regime, can occur due to abrasive and adhesive wear. Typically these operating conditions are avoided. In some application with high loads and low speeds (e.g. wind turbines) this cannot be prevented. Therefore, lubricants with suitable properties are used in these applications and inhibit wear due to modifications at the surface of the roller bearings. This is normally achieved by additives mixed with the base oil. Chemical and physical interactions between the lubricant and the bearing surface, enhanced by high pressures and stresses, lead to modifications and the occurrence of a non-metallic layer at surface of the rolling bearing. This processes result in the development of the so-called boundary layer.

This layer can inhibit the direct steel contact of the mating elements (roller and washer) and reduce abrasive and adhesive wear. Hence, the layer is also called anti-wear layer or anti-wear film. A prediction whether a protecting layer is formed or not is not yet possible. The understanding of the chemical processes between the additives and the surface, which lead to the layer formation, is not sufficient for this purpose. Therefore, experimental testing is needed for a qualification of the wear protection ability of different lubricants up to today.

In this study, the formation of anti-wear layers is investigated for cylindrical roller thrust bearings. The influences of the operating conditions (load, speed, temperature) and the lubricant properties (additive concentration, additive structure) on the layer build-up is determined in a rolling bearing test rig. As additive, the commonly used zinc dialkyldithiophosphate (ZDDP) is applied.

1.1 Tribological boundary layers

Boundary layers are a system of individual layers divided into the inner and the outer boundary layer. The inner boundary layer describes a finely crystalline area which results from the surface finishing process at the end of machining or the high stresses under severe operating conditions. This part is also known as tribomutation layer and has a thickness of 400 nm to 5 µm depending on the acting mechanical strains. Due to the finely crystalline characteristics, the mechanical properties can differ from those of the base material. [1]

The outer boundary layer is a multi-layer system itself and generally thinner than the inner boundary layer. After machining, an oxide layer of a few nanometres develops in new rolling bearings on top of the metal surface by oxidation processes at air environment. Chemical reactions between with the lubricant additive and the base material result in an additional layer in this system, the so-called reaction layer. This layer is often described as a glass-like structure consisting of different reaction products of the chemical reactions between lubricant and material elements. [2][3] Both layers can mix and circulate in the outer boundary layer. Then, a rigid separation is not possible. On top of these layers, lubricant components can adsorb. As they are mostly weak bonded, these components are removed during sample preparation for micro analytical analyses and thereby not detectable. [1] The whole boundary layer system is shown in figure 1.

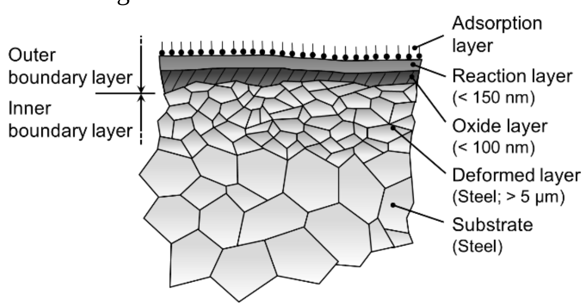

Figure 1. Boundary layer system

1.2 The additive zinc dialkyldithiophosphate (ZDDP)

The risk of wear in the heavily loaded tribological contacts of machine elements is always present when direct contact of the solid bodies occurs. Hence, so called anti-wear (AW) and extreme pressure (EP) additives are added to the lubricant. These additives form the reaction layer of the boundary layer system and inhibit the direct steel-steel contact, reducing abrasive and adhesive wear. One often applied additive with AW- and EP-characteristics is zinc dialkyldithiophosphate (ZDDP). It is used since several decades and also provides properties as antioxidant and corrosion inhibitor. [2] ZDDP is a metal organic compound and has a good solubility in mineral oils. The alkyl group of ZDDP can vary in length and structure, influencing the thermal and hydrolytic stability and thus the AW/EP performance. The structure of the alkyl groups (R) can be either primary, secondary or aromatic (s Figure 2).

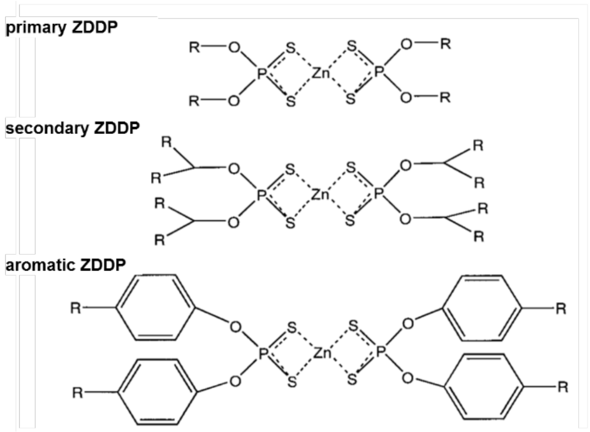

Figure 2. Structure of ZDDP (adapted from [4])

The thermal and hydrolytic stability rises with increasing chain length while the reactivity is reduced. [5] In this study, the ability to form a wear inhibiting reaction layer is compared between a primary ZDDP with mainly short chains and secondary, long chain ZDDP.

2. Experimental

2.1 FE8-test rig

Concerning their wear prevention capability, lubricants are tested in tribometers with simplified contact condition or test rigs, in which machine elements can be applied. Due to the high complexity of the contact conditions in machine elements, practical information on wear can only be obtained by the direct testing of such components.

The characterisation of a lubricant‘s wear behaviour in rolling bearings is often done in the FE8 test rig. Two cylindrical roller thrust bearings of type 81212 are used for the classification tests due to high percentage of slippage between washer and roller. The bearing and the qualitative sliding speed is shown in figure 3.

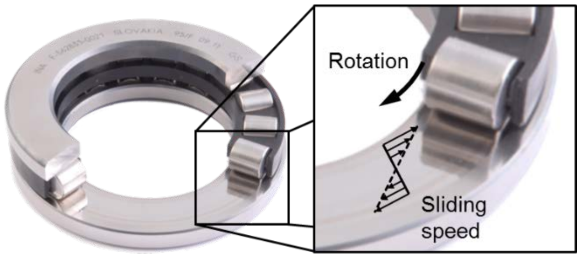

Figure 3. Cylindrical roller thrust bearing 81212

The standardised test procedure according to DIN 51819-3 [6] is performed under wear critical operating conditions in the boundary lubrication regime. The standard test is run at a temperature of 80 °C, a rotational speed of 7.5 rpm and an axial load of 80 kN, which corresponds to a Hertzian pressure of 1920 MPa. The wear mass is used to classify the lubricant’s wear protection capability and measured after 80 hours with a precision of 1 mg. According to DIN 51517-3 [7] the wear mass of a roller set must be less than 30 mg for the approval as CLP oil. A more precise classification can been specified. In this case, a lubricant provides very good wear protection if the weight loss at the roller set is less than 10 mg. A weight loss of over 100 mg is considered as very high wear. [8]

Well-developed lubricants with adequate anti-wear properties will show a negligible wear loss during the test due to the formation of the anti-wear layer induced by chemical reactions between the lubricant additive and the bearing surface.

In this study, a modified FE8 test rig is used for the tests on the formation of anti-wear layers. The axial load can be applied dynamically and different operating conditions can be driven during one test. The test rig setup is shown in figure 4.

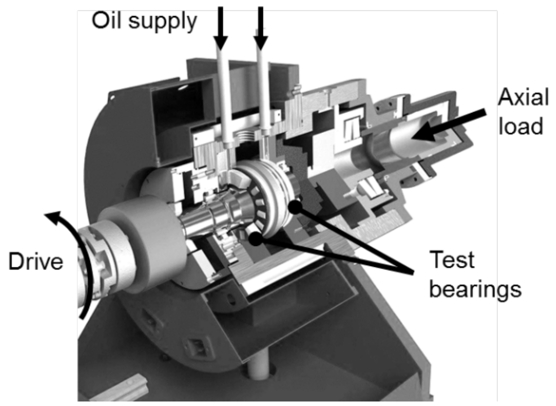

Figure 4. Modified FE8 test rig

The layer formation can be monitored online by the measurement of the contact resistance. This measurement can provide information on the lubrication regime and the current state of the boundary layer. In both cases, the change of the ohmic resistance is caused by a missing direct steel contact between the rolling bearing elements. In the full lubrication regime, the lubricant separates both surfaces resulting in a higher resistance. In the second considered case, the outer boundary layer, formed by the additive ZDDP, has a higher ohmic resistivity than the steel substrate. When the layer is formed on the complete surface the contact resistance will rise even if the bearing is operated under mixed friction conditions. Furthermore, the information of the contact resistance can give an indication on the current wear status. If a resistance is measured, the surfaces are effectively protected from wear.

2.2 Experimental procedure

In this study, the formation of anti-wear layers depending on the influencing parameters, operating condition and oil composition, is analysed. Therefore, a test procedure is applied, which is able to define the limit of the protective layer build-up. All influencing parameters are hold except for the rotational speed. This parameter is reduced respectively raised till the limit is reached. Figure 5 shows a results of this procedure. The rotational speed is reduced in three steps and for the last test (right), wear could be observed.

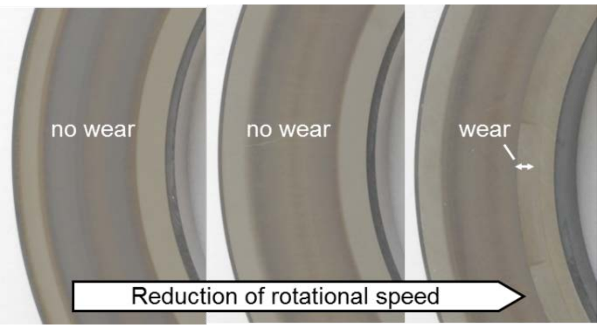

Figure 5. Anti-wear layer formation

After the speed limit is found, one of the other parameters is varied and the procedure is repeated. To cover a large area of the operating conditions, the contact pressure is modified from 500 MPa to 2000 MPa and the rotational speed ranges between 7.5 rpm and 75 rpm. The tests are conducted at a mass temperature of 80 °C, 60 °C or 40°C. The test were driven as short test with a duration of 2h.

The second influencing factor of the layer formation is the applied oil in the test. The oil composition in this study is varied regarding the additive concentration and the additive structure. A mineral oil of class ISO VG 100 is used as base oil and mixed with the ZDDP. The concentration is varied from 200 ppm to 1750 ppm phosphorus in the oil. According to the API SN standard, the concentration of phosphorus in engine oils must be between 600 ppm and 800 ppm. [9]

Beyond that, two different additive structures are investigated in this study. One structure has primary alkyl groups with mainly short chain lengths, the other one is a primary ZDDP with long chain alkyl groups. As mentioned before, the structures have different properties concerning the thermal stability and the reactivity thus leading to different operating conditions needed for the layer formation.

The identification of a complete layer formation is done in three steps. Firstly, an optical evaluation is done after the test. If a layer is formed the surface is discoloured and if wear occurred there is usually a shiny surface. This behaviour can be seen in figure 5. Secondly, the wear mass is measured. If there is no weight loss a protecting layer was formed. Finally, microanalyses are performed with the electron probe microanalysis (EPMA). This can provide information on the chemical elements at the contacting surfaces of the bearing. Chemical elements of the additive, like phosphorus, sulphur and zinc, can be found. A typical element distribution is shown in figure 6. At the inner part of the raceway no layer was formed, corresponding with the microanalysis.

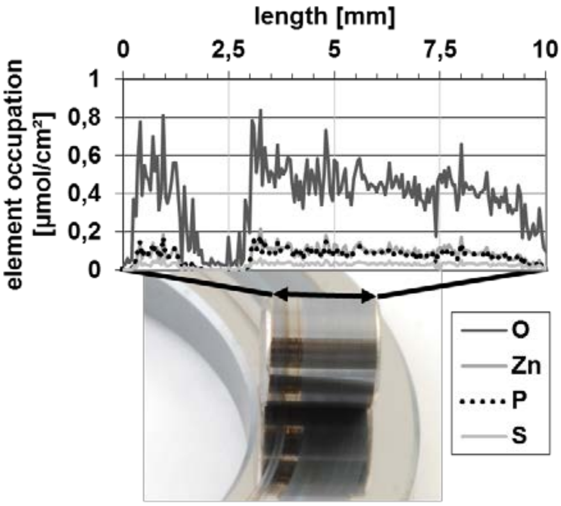

Figure 6. Microanalysis of formed anti-wear layer

3. Results and discussion

3.1 Influence of additive concentration and additive structure

The first tests were conducted with the variation of additive concentration and rotational speed. The load was held at 80 kN (1920 MPa) and the temperature at 80 °C. The results of the layer formation tests are shown in figure 7 for the short chain ZDDP and in figure 8 for the long chain additive. Two areas can be noticed to describe the limit of a protective layer build-up. At high additive concentrations a constant rotational speed is required for the layer formation. The second area is characterised by a rising required speed when reducing the additive concentration. The limit can be described by a linear relation between rotational speed and additive concentration. Comparing both structures, differences in the size of both areas can be seen. The area of the constant minimum limit reaches to smaller concentration for the long chain ZDDP. Then the limit increases much faster and meets the limit of the short chain ZDDP at a minimum concentration of 200 ppm phosphorus.

The increase of the rotational speed can be linked to a raising lubricant gap height at low additive concentrations. This implies a higher oil volume in the contact area and may compensate the missing additive amount due to reduction of the concentration.

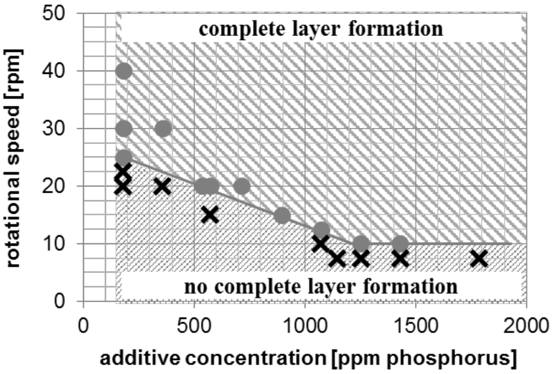

Figure 7. Influence of speed on anti-wear layer formation for short chain ZDDP

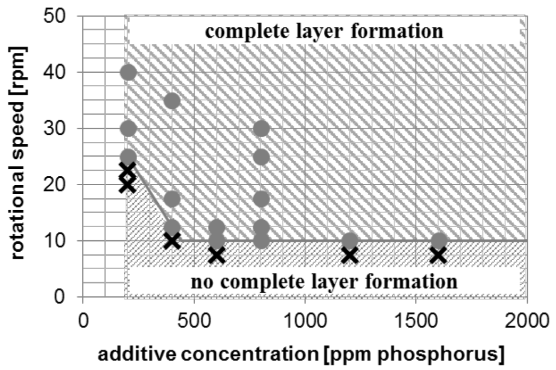

Figure 8. Influence of speed on anti-wear layer formation for short chain ZDDP

3.2 Influence of contact pressure

As a second influencing parameter on the layer formation, the contact pressure is varied in this study. The tests were conducted for selected concentrations and at a temperature of 80 °C. The pressure is reduced from the 1920 MPa to 500 MPa for the short chain respectively to 1000 MPa for the long chain derivative. The results for the short chain ZDDP describe a decreasing limit with reduced contact pressure. This limit is shown in figure 9 for two representative concentrations.

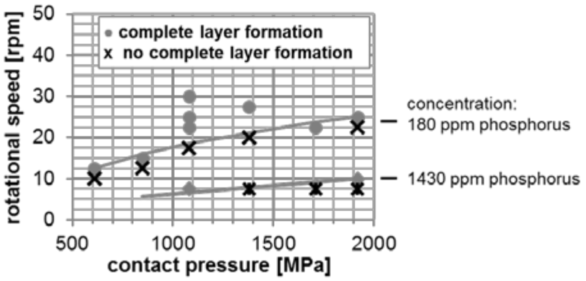

Figure 9. Influence of contact pressure on anti-wear layer formation for short chain ZDDP

For the additive structure with the long chain alkyl groups the limit is presented in figure 10. Some differences can be seen compared to the results of figure 9. In contrast, no complete anti-wear layer was formed during the test at low contact pressures. Even higher rotational speeds make no impact although this was a good opportunity at lower concentrations, as shown in chapter 3.1.

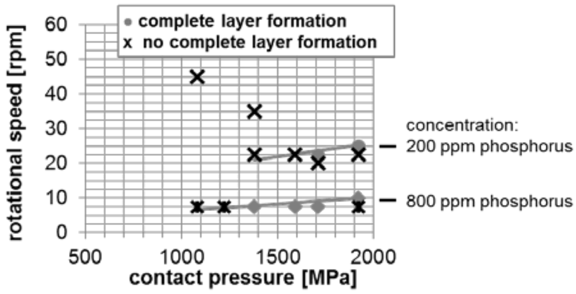

Figure 10. Influence of contact pressure on anti-wear layer formation for short chain ZDDP

The grey lines drawn in both figures represent a constant lubrication gap height calculated with Dowson's formula. The considered test conditions are located in the boundary friction regime, where that formula is not valid. But this consideration can give a good opportunity to compare two operating conditions qualitatively.

As can be seen, a correlation between the limit of the layer formation and the lubricant gap height is possible. Thereby, the same lubricant volume is needed for a layer formation at each concentration. Taking this and the increase of the required rotational speed at low additive concentrations into account, a dependence of the layer formation on the additive amount in the contact area may be possible. As the bearings are operating under boundary friction conditions a direct correlation between the gap height and the additive amount is not allowed due to roughness effects. The results of this consideration are still pending and published later. Therefore, a correlation for the layer formation is only possible between the lubrication gap height and the additive concentration. The relation is shown for both additive structures in figure 11 and figure 12.

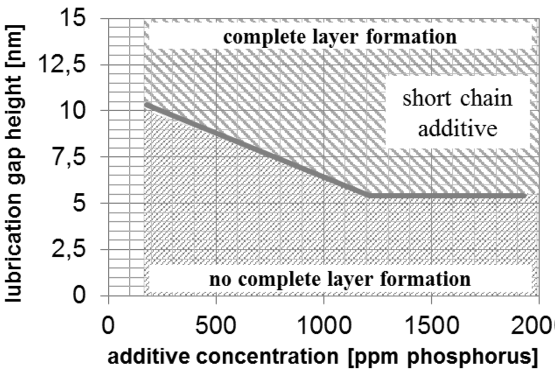

Figure 11. Limits of the anti-wear layer formation depending on lubricant gap height for short chain ZDDP

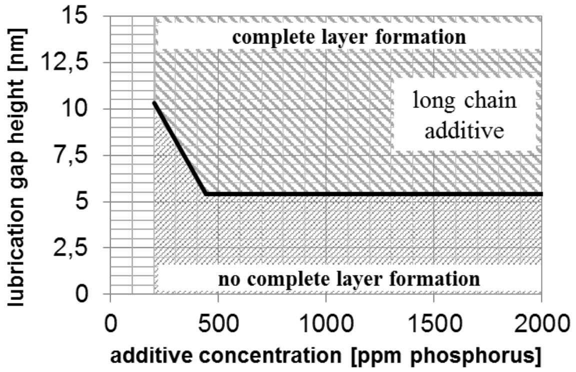

Figure 12. Limits of the anti-wear layer formation depending on lubricant gap height for long chain ZDDP

3.3 Influence of additive structure

In figures 11 and 12, two other specifics of the layer formation are obvious. On the one hand, a minimum gap height is always required even at high concentrations. This can also be linked to a required additive amount in the contact. Due to the high percentage of the solid body contact, the lubricant volume in the contact area is so small that the amount of additive molecules is not sufficient for a complete layer formation.

On the other hand, the limiting lines of both structures show a significant difference: The limit of the long chain derivative remains at the minimum gap height even at smaller additive concentrations. Comparing both structures, the short chain molecules have about half the length of the long chain ones. This cannot explain the behaviour at small concentrations if the limit is correlated to the additive amount. But former micro analyses of such layers can offer an explanation. Inacker et al. [10] analysed the formed reaction layers of ZDDPs with different alkyl chain lengths. They showed that the structural design is different. The layers formed by short chain ZDDP are thick and soft, whereas long chain additives form a rather thin and hard layer. This behaviour can give following explanation for the results in this study. Less additive molecules are required for the formation of thin layer, what explains the minimal required lubricant gap even at low concentrations for the long chain derivative.

3.4 Influence of temperature

A variation of the temperature has been done for the short chain additive between 40 °C and 80 °C. At high pressures (1920 MPa) a protective layer can be formed even at 40 °C. The limits and a possible compensation curve are shown in figure 13. Here the compensation curve also represents a constant gap height. This support the thesis that the amount of additives in the contact area is essential for the successful layer formation.

Further tests at low temperatures (60 °C) and lower contact pressures (1450 MPa) showed that a protective layer build-up is no longer possible. The limits of the layer formation are reached.

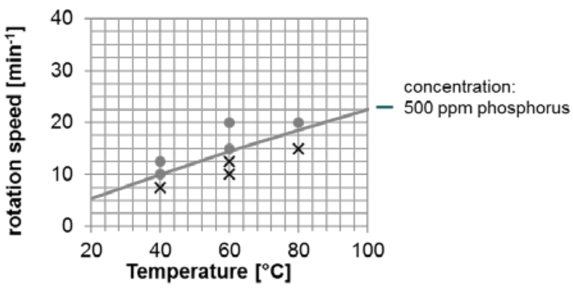

Figure 13. Anti-wear layer formation for short chain ZDDP at a contact pressure of 1920 MPa

Next to the possible limit due to the additive amount in the contact, another limiting factor of the layer formation can be detected. No protective film was formed at low pressures and temperatures. A possible explanation for this behaviour can be the chemical reactivity of the contact area, which must exceed a critical level for the layer build-up. Two effects affect this reactivity. The solid body contact in the boundary friction regime leads to local frictional heating. Adding this to the mass temperature applied in the test, a higher local temperature and therefore a higher reactivity is reached. Besides, tribochemical interactions can be induced due to tribostresses in the contact area and these tribostresses are directly coupled to the contact pressures. Therefore, both, the higher temperatures and contact pressures, enhance the reactivity of the system and accelerate the chemical reaction, on which the layer formation is based. [3] [11]

Differences in the required contact pressure were shown in figures 9 and 10. The layer build-up for the long chain additive is limited while no limit was found at 80°C for the short chain derivative. This behaviour can be coupled with the thermal stability, which is higher for the long alkyl groups. At 40°C and a Hertzian contact pressures of about 1450 MPa, the limit is also reached for the short chain ZDDP. For a protective anti-wear layer formation, all described limits must be exceeded.

5. Conclusions and outlook

Boundary layers in rolling bearings can inhibit wear under severe operating conditions in the boundary friction regime. These anti-wear layers are formed by chemical reactions of the lubricant's additives and the steel of the contacting surfaces of the rolling bearing. With this, the direct steel contact is prevented thus reducing adhesive and abrasive wear. The mechanisms of the layer formation and the chemical reactions in highly loaded machine elements are mostly unknown. Nevertheless, the wear-free lifetime of the elements must be ensured. This is often realised by a high percentage of additives in the lubricant. For an additive reduction, the influencing parameters on the protective layer formation must be identified. The results of this study provided a contribution to this issue.

Tests with cylindrical roller thrust bearings were conducted in a modified FE8 test rig. Limits of the anti-wear layer formation were identified by variation of the operational parameters rotational speed, load and temperature and the additive parameters concentration and structure. The analysis of the results leads to two requirements which must be met for a protective layer formation.

Firstly, the amount of additive molecules must be sufficient for a complete layer formation. This can be achieved by matching the lubricant gap height and the additive concentration.

Secondly, the reactivity of the system must permit enough chemical reactions between the additive molecules and the surface for the layer formation.

Both requirements are deduced as qualitative values and must be specified with physical or chemical reference values in a next step. In addition, the influences of higher temperatures and the sliding speed are still unknown and must be identified in further tests.

Acknowledgements

The authors would like to thank the “Deutsche Forschungsgemeinschaft” (DFG) for the funding of the project Ja1940/2.

References

[1] G. Burghardt et al.: Influence of run-in procedures and thermal surface treatment on the anti-wear performance of additive-free lubricant oils in rolling bearings, Wear, 328-329 (2015), 309–317

[2] H. Spikes: The history and mechanisms of ZDDP, Tribology Letters, 17 (2004) 3, 469-489

[3] S. Bec et al.: Relationship between mechanical properties and structures of zinc dithiophosphate anti-wear films, Proc. R. Soc. Lond. A (1999) 455, 4181–4203

[4] R. Heuberger: Combinatorial Study of the Tribochemistry of Anti-Wear Lubricant Additives, PhD thesis, ETH Zurich, 2007

[5] T. Mang, W. Dresel: Lubricants and Lubrication, Wiley-VCH, 2001

[6] DIN 51819-3: Testing of lubricants - Mechanical-dynamic testing in the roller bearing test apparatus FE8 - Part 3: Test method for lubricating oils, axial cylindrical roller bearing, 2005

[7] DIN 51517-3: Lubricants - Lubricating oils - Part 3: Lubricating oils CLP, Minimum requirements, 2014

[8] A. Stratmann et al.: Formation of Anti-Wear Films in Rolling Bearings due to Run-in Procedures, Proc. of WTC 2013, Torino, 2013

[9] API SN standard

[10] O. Inacker et al.: Triboschutzschichtcharakterisierung, FVA-Heft 595, 2000

[11] R. Heuberger et al.: Pressure Dependence of ZnDTP Tribochemical Film Formation: A Combinatorial Approach, Tribol Lett (2007) 28:209–222