Examination of friction and wear of a 100Cr6 ball against a bearing ring in a micro-pin-on-disk tester

N. Bader[1], F. Pape[1], H. H. Gatzen[2] & G. Poll[1]
[1]*Institut fuer Maschinenkonstruktion und Tribologie, Leibniz Universitaet Hannover, Germany*
[2]*Institut fuer Mikroproduktionstechnik, Leibniz Universitaet Hannover, Germany*

Abstract

Understanding the wear and friction phenomena in bearings is of key importance for the reduction of friction and wear. Boundary layers formed by oil additives during operation may significantly influence the frictional behaviour. To investigate the behaviour of such layers standardised test runs with cylindrical roller thrust bearings were conducted using differing oils with varying additivation. For these tests a FE-8 test rig for characterisation of rolling contact bearing lubricants was applied. As oil a low reverence and high reverence oil, as well as differently additivated oils were used. These oils may result in different boundary layers on the wear tracks. To analyse the frictional behaviour of these layers on the bearing surface, a micro-pin-on-disk tester was used under very low load. The contact of a spherical pin (made of 100Cr6) on a bearing disk (also called washer) without lubrication was examined. As a counterpart the bearing disks were used after the run in a bearing test rig under various oils, unused, and etched on the surface. Before application on the micro-pin-on-disk tester, all adhesive oil was removed. During the tests the coefficient of friction was monitored. The tests were performed at a rotational velocity of 1 min^{-1}, the load was 27 mN.

Keywords: 100Cr6 bearing steel, thrust bearing disk, polymer transfer films, micro-pin-on-disk tester.

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1 Introduction

For a reliable function of bearings, a reduction of wear and friction is of utmost importance. The tribo behaviour is strongly influenced by the boundary layers formed on the contacting elements. An efficient way to analyse the frictional properties of these layers is to slide a pin in the form of a ball with a diameter in the sub-millimetre range over the surface and to record the forces occurring. Such tests were conducted in a micro-pin-on-disk tester. These micro-pin-on-disk tests allow the investigation of the gap between classical AFM (atomic force microscopy) and macroscopic wear tests. Tribological investigations by Meine and Santner revealed a dependence of the microwear on the surface roughness [1, 2]. Even surfaces with an average roughness R_a of as low as 1.4 nm were found to be subjected to wear [3, 4]. Friction on the micro scale of ceramic surfaces was measured by Bhushan and Sibleya [5].

Archard and Hirst [6] investigated the influence of contact area and load of the unlubricated contact of steel. While steel rolling contact bearings are typically used under the lubrication of oil or grease, unlubricated contacts are of substantial scientific interest. Surfaces under relative motion without grease- and oil lubrication can be found in aerospace application. In such an application, oxide films, humidity, and intermediate materials significantly influence the occurring friction [7, 8]. For high temperature applications, graphite and molybdenum-disulphide coated bearings are in use [9].

A typical bearing steel is 100Cr6 (German standard corresponding to AISI52100). On 100Cr6 bearing steel, Frisch *et al.* [10] studied tribomechanical and tribochemical processes. Under nitrogen as atmosphere a hardening of the surface could be detected, under oxygen both wear, oxidation were observed. Klaffke *et al.* investigated the contact between 100Cr6 steel and SiC ceramic [11]. A high influence of humidity, load, and the kind of ceramic was observed [12].

According to Bhushan (figure 1) there are three regions of contact. At low contact pressures the contact is elastic and affected by oxide films. At medium contact pressure ploughing occurs and the coefficient is higher. At high contact pressure the coefficient of friction reduces due to roughening and debris effects but stays higher than in case of low contact pressure. It was observed, that in case of unlubricated contacts, oxide films reduce the friction [6, 14–16]. The surface hardness of the contact partners also influence friction and wear [17]. Additionally, the surface cleanliness, sliding speed, and temperature are of importance [13]. When conducting a micro-pin-on-disk test any one of these phenomena may occur. The results gained in micro-pin-on-disk tests may also be influenced by layers formed during previous lubricated operation of one of the contacting bodies.

Tohyama *et al.* presented that polymer additivated oil can reduce the frictional force in a block against ring test. With ToF-SIMS measurements on the surface, polymer films could be proven. Based on these results, Tohayama introduced a model of adsorbed polymers on metallic surfaces (shown in figure 2) [18].

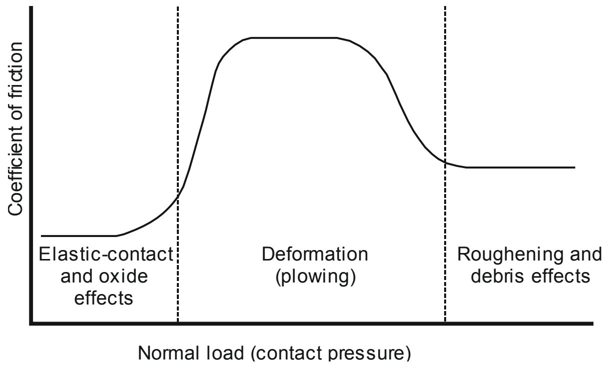


Figure 1: Influence of contact pressure on the friction for metallic contacts [13].

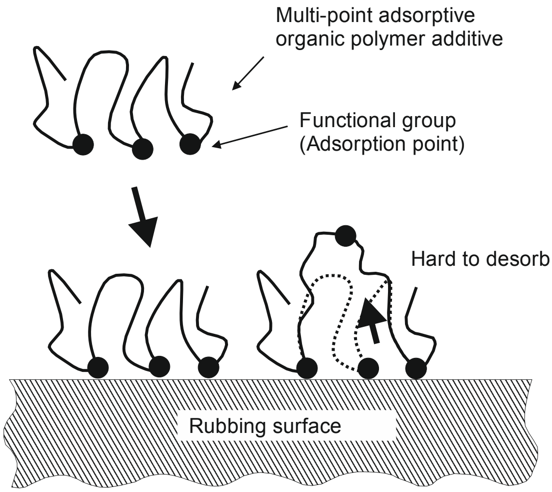


Figure 2: Model after Tohayama *et al.* [18] of adsorbed polymers on metallic surfaces.

Wiendl *et al.* [19] investigated the correlation of chemical processes and surface layers for additivated greases. For this purpose nanoindentaional studies on bearings and ToF-SIMS measurements were performed on used rolling bearings. It could be shown that antioxidants reduce the oxidation of the grease and have influence on surface layers. Effects of polymer additivated greases on surface layers were investigated by Gatzen *et al.* [20]. Rolling bearings were analysed applying nanoindentational tests and ToF-SIMS. The formation of surface layers could be shown and effects on the surface roughness and hardness could be detected.

2 Experiment

The experiment consists of two parts. For the first part of the experiment cylindrical roller thrust bearings were subjected to life tests. Both the rollers and the disk (also called washer) materials were 100Cr6 (German standard). The bearings were oil lubricated; these oils contained viscosity-index improvers (VI-improvers). VI-improvers consist of polymer chains which can attach to metallic surfaces in conjunction with other additives. After reaching the desired running time, the systems were disassembled and in the second part of the experiment the disks were subjected to a micro-pin-on-disk test. To investigate the micro contact conditions, spherical 100Cr6 pins were tested against the surfaces of the cylindrical roller thrust bearing disks (also called washers) without lubrication.

2.1 Bearing life test

Each of the axial bearings subjected to the life test was lubricated with a specific oil and mounted in the FE-8 test rig. Figure 3 depicts the setup of the test rig. The test is specified in the standard DIN 51819 for the mechanical-dynamic measurement of rolling contact bearing lubricants. The bearings were pre-loaded by disk springs. During the test oil was supplied at a constant flow rate of 0.1 l/min. The test head was ventilated to stabilise the bearing temperature.

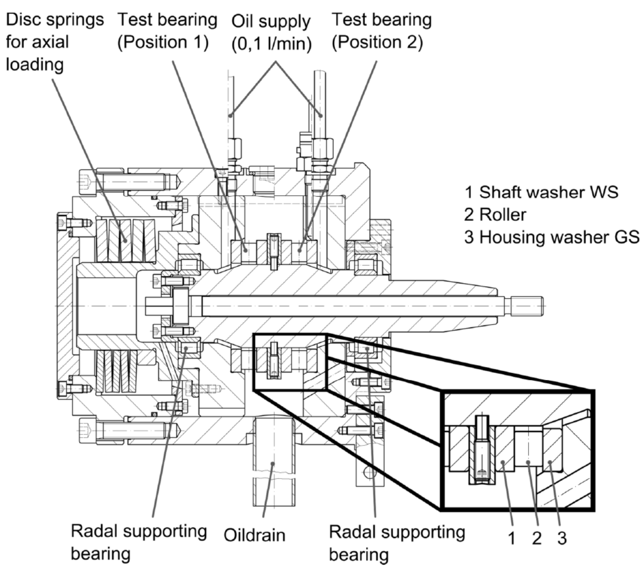


Figure 3: Head of FE-8 test rig for characterisation of rolling contact bearing greases.

For the FE-8 tests an axial load of 60 kN was used. A run in for 24 h at 500 rpm with subsequent 176 h test run at 750 rpm was conducted. A bearing failure before reaching the desired total of 200 h running time was determined by vibrational measurements.

During the test the torque and temperature were measured. After concluding the tests a portion of the bearing was subjected to micro-pin-on-disk tests.
The disks tested are presented in table 1. For application the reference oil high ref (FVA3+A99) and low ref, a manual transmission oil (MTF) and a double clutch transmission oil (DCT) were used. The MTF and DCT oils were investigated in three formulations, Serie, Kand, and Ref. The Serie formulation is a standard oil for the respective application already on the market while the Ref is a lubricant with reduced viscosity but identical additivation of the Serie. The Kand also has a reduced viscosity and in addition different additives containing VI-improvers. The chemical composition of the additivation was not disclosed due to proprietary information of the supplier. A new bearing disk was investigated and a second new bearing disk was etched in Ar plasma and tested under inert atmosphere as reference in the micro-pin-on-disk test.

Table 1: Tested disks.

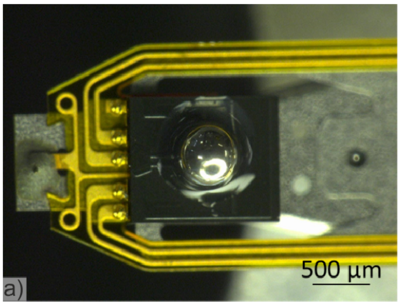
Lubricant	Running time in h
DCT Ref	200
DCT Kand	200
DCT Serie	200
MTF Kand 90°C	200
MTF Ref	200
Low Ref	56
High Ref	200
MTF Kand 100°C	48
new bearing	-
Plasma etched bearing tested under argon atmosphere	

*bearing at pos. 2 investigated due to pittings on bearing pos. 1

During the tests a temperature of 100°C was reached at the bearing using ventilation of the test head. The bearings with MTF Kand only reached a temperature of 90°C using ventilation. Subsequently this test was repeated with addition of external heating so that 100°C was reached. This in turn resulted in a bearing failure due to pittings on the raceway after 48 h compared to 200 h running time under ventilation.

2.2 Micro-pin-on-disk test

For the micro-pin-on-disk test, a modified spin-stand supplied by CETR (now Bruker) was used. The test stand was originally developed to investigate the head-to-disk interface of a hard disk drive (HDD) [21]. Figure 4 depicts the micro-pin-on-disk components. As test specimen, a 100Cr6 ball was attached to the slider of a HDD recording head (head gimbal assembly – HGA) using adhesive (Fig. 4a)), which was mounted on the testers arm. A vertical displacement allows the application of the desired normal force. Fig. 4b) depicts slider and flexure mounted to the test arm representing the stationary part of the pin-on-disk tester. Integrated in the arm are strain gauges which provide force signals during the test when the slider is in contact with the rotating disk as well as acoustic emission sensors. As a counterpart, a 100 mm diameter axial bearing disk was used, as depicted in fig. 5. Figure 5a) shows a photograph of the test setup, and fig. 5b) a schematic representation. To attach the bearing disk (rotating during the test) to the micro-pin-on-disk tester, a special holder was used.



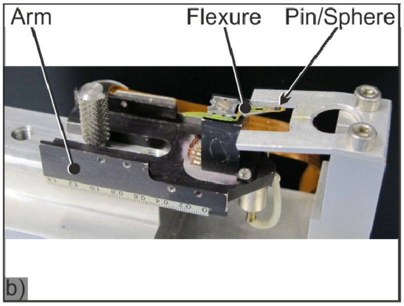
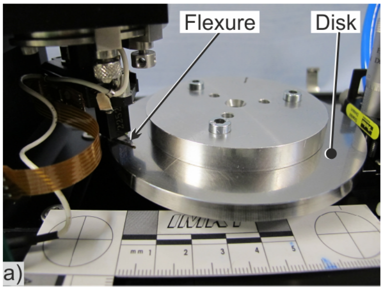


Figure 4: Components of the pin-on-disk Tester; a) 100Cr6 ball glued on flexure, b) arm with mounted flexure.



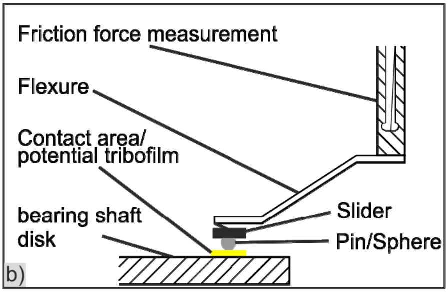


Figure 5: Pin-on-disk test stand, left: Thrust bearing disk mounted on pin-on-disk tester; right: overview of test.

The tests were conducted for a time of 300 sec at constant speed of 1 rpm, on a radius of approx. 0.035 m. The sliding speed was 0.004 m/s, the load caused by the flexure 27 mN, and the contact pressure 13.75 N/mm^2. The parameters are chosen to allow a stable test without significant wear on the ball, to achieve resilient results for all disks. No lubricant was applied during the tests. The axial bearing was cleaned before test with n-hexan, to remove all organic adhesives.

Exemplarily, fig. 6 depicts the friction for the 500 μm ball tested against a thrust bearing disk which ran with DCT Ref (TBA 021). The friction reaches a stable condition, where it shows little fluctuation, due to the surface roughness and minimal misalignment.

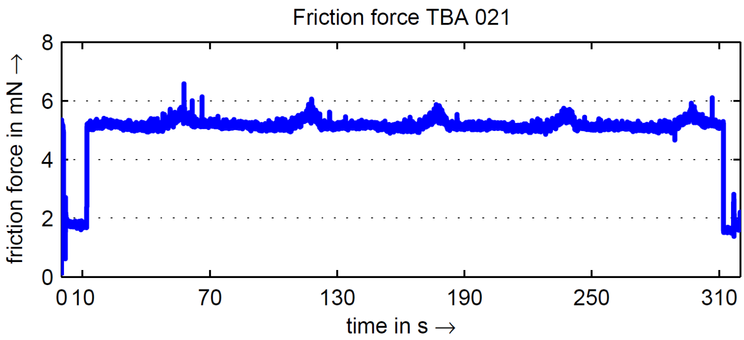


Figure 6: Measured friction of exemplary run of 100Cr6 ball against disks.

For all bearings, the coefficient of friction was measured. The arithmetic mean value was calculated, and is depicted for all disks in fig. 7. The highest friction of the disks with previous lubrication was found for the disk used with low ref oil. The coefficient of friction (COF) was approx. 0.092. This friction is on the same level as the measured values of the new, unused disk (μ=0.089). In this case no indication for a formation of a friction reducing layer could be found. The etched disk under inert atmosphere shows the highest friction reaching a COF of 0.108. Thus the new bearing disk which was run under normal atmosphere and with normal cleaning already shows a reduced friction probably due to oxide layers. Frisch *et al*. [10] found a significantly higher COF of 0.5 in a dry 100Cr6/100Cr6 contact under air atmosphere but utilised a set up with larger forces and contact areas (pin with 4 mm diameter). In case of a HDD contact similar to the discussed experiment Bhushan [22] found a comparable COF of 0.15 for unlubricated contacts with similar environmental conditions (air with 50 % humidity). Pape [23] achieved starting values of 0.14 for the COF in nanoscratch tests on 100Cr6 steel which concurs with the values measured in the experiment described above.

The frictional values for high ref and all DCT oils are at approximately 0.08. The friction is not as high as for the unused disk, but in a similar region. The frictional forces of the MTF Kand disk which ran at 100°C are in the range of the DCT used disk as well with a value of approx. 0.081. A difference between the MTF Kand and Ref oil is visible with the MTF Ref only reaching 0.069. For the disk running with MTF Kand at 90°C the value of friction is lower (0.071) than for the comparable disk with the same MTF Kand running at 100°C. The lower frictional force can be referred to the formation of polymeric boundary layers on the surface. The MTF Kand at 90°C however delivers similar COF as the MTF Ref although both formulations possess different additive formulations.

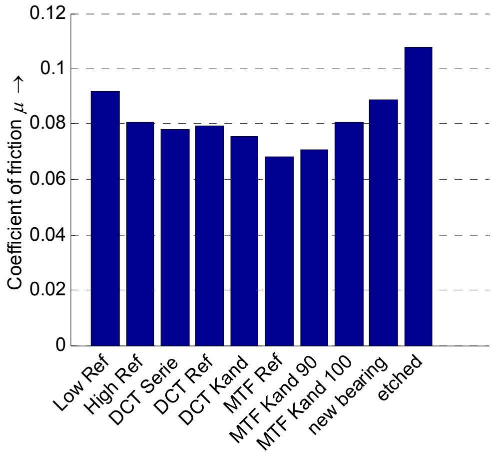


Figure 7: Frictional forces for the tested disks.

2.3 A brief excursion: chemical analysis of boundary layers by ToF-SIMS

To gain insight into possible tribochemical layers ToF-SIMS investigations of the complementary bearing disks (i.e. housing disks; the shaft disks were used in the micro-pin-on-disk tests) were conducted. The method employed in ToF-SIMS is a mass spectroscopy of secondary ions which have been desorbed from the sample surface [24]. These measurements are repeated after sputtering away a layer of the surface. Thus profiles of molecules/elements can be gained at different depths within the sample. The presented measurements were conducted at the University of Munster.

The bearing disks were cut and subsequently cleaned with n-hexane to remove adhesive molecules and oil residue. Figure 8 shows a bearing segment with the positions of investigation. Due to the fact, that friction measurements with the micro-pin-on-disk were conducted on the racetrack only positions 1, 3,

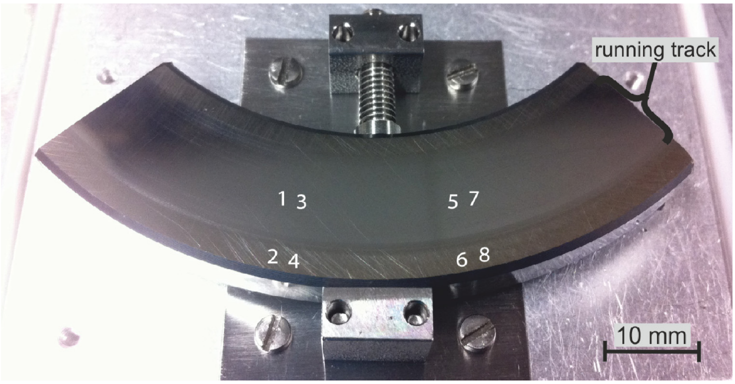


Figure 8: Positions for the ToF-SIMS measurements.

5, and 7 are discussed in this paper. The measurements at positions 3 and 7 were made with negative ions as primary ions, while at positions 1 and 5 positive ions were used.

An analysis of the bearing disks run in the DCT and MTF oils using TOF-SIMS reveals a possible tribolayer. This is visible due to the sharp drop of signal intensity of the SO_3-signal observed in fig. 9 at about 100 s sputtertime (sputtertime correlates depth). Furthermore, the signals of MTF Kand at 90°C and 100°C differ, supporting the theory that different layers formed due to temperature differences.

This difference is further supported by the PO_3 signal in fig. 10. The signals for MTF Ref and MTF Kand at 100°C reach similar maximum levels. The MTF Ref shows a broader level leading to the assumption that thicker layers were formed.

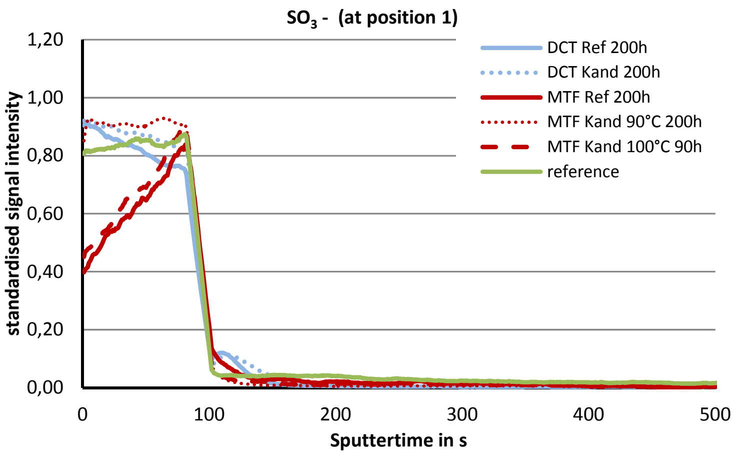


Figure 9: ToF-SIMS signal of SO_3.

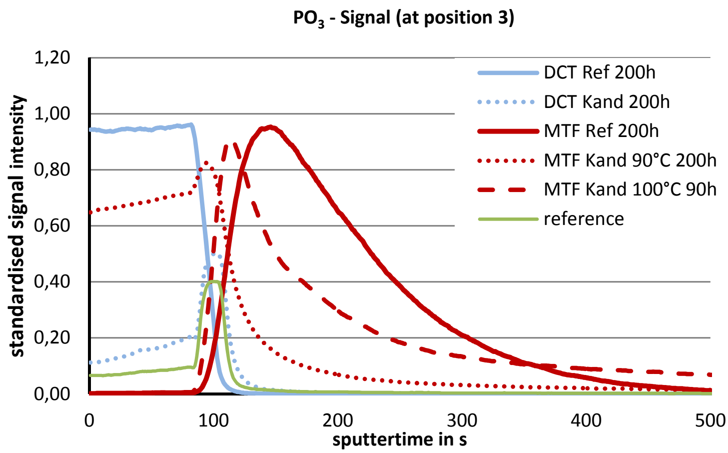


Figure 10: ToF-SIMS signal for PO_3.

This may be the reason which leads to the different friction coefficients in the micro-pin-on-disk test. The DCT Ref signal shows a constant high level up to a sputter time of about 100 sec. Thus it seems that the possibly formed layers also significantly differ in the chemical composition within the layer.

Further element concentrations were also investigated (P, PO, S, SO, SO_2, PSO, PSO_2, Ca, CaP). Several elements show differences in the formed layers or chemical surface properties. The shown signals were chosen due to the fact that their origin is mostly thought to be due to lubricant additives. Further research into the layer compositions is ongoing but the present analyses show that chemical differences are present on the disks exhibiting different frictional behaviour in the micro-pin-on-disk tester. Gatzen *et al.* [20] proved the formation of a LiO^- outside boundary layer and a FeO_2^- inner boundary layer based on TOF-Sims measurements. Additionally it was shown, that the greases containing polymers influence the COF during the tests.

3 Conclusion

The function of a HDD tester for micro tribological tests of bearing surfaces was presented. Thrust bearing shaft disks (also termed washers) were investigated after running in a test rig. For this measurement a relative testing length of 300 sec. at 1 rpm provides reliable frictional data. It could be shown, that for the disks used with MTF oil, a significantly lower COF, compared to the other oils, could be detected.

For this oil, a difference in friction could be detected for the disk running at 90°C compared to the one running under 100°C. The friction for the disk running at 90°C was lowest. It can be concluded with regard to ToF-SIMS investigations, that the formation of friction reducing layers is combined with a lower temperature in the test rig or that the tribolayers formed at 100°C are not stable. This could be supported by investigating the running times until failure in the FE-8 test.

Combining a rolling contact bearing life test and a following micro-pin-on-disk test reveals interesting aspects of the boundary layers formed during the life test run and the influence on the tribological behaviour. It could be demonstrated that virgin bearing has a high friction (0.089) in the pin-on-disc test, while some of the oils (containing additives) reach lower values. Particularly a group of bearings (DCT and MTF Kand at 100°C) the COF is only 0.08 while the unadditivated oils reached 0.089 which hardly differs from a new bearing. Etching a virgin bearing and keeping it under a non-oxidising atmosphere demonstrates that rolling contact bearings are subjected to modifications initiated by the environmental conditions. Additional information regarding chemical influences could be gained by ToF-SIMS analyses.

It could be proven, that not only the mechanical properties of the boundary layers (hardness and Young's Modulus) are influenced by additivation, as shown previously by Wiendl *et al.* [19] and Gatzen *et al.* [20]. In addition, an influence on the friction coefficient could be proven, which was not possible to be measured by nanoindentational studies as the nanoindenter tip penetrates possible boundary layers at the surface. With the introduced setup, the tip remains on the surface without scratching.

It must be noted, that the measured COF in the micro-pin-on-disk tester cannot be directly compared to torque measurements gained in the FE8 test. This is due to the different kinematics as well as the dry contact in the micro-pin-on-disk tester compared to the lubricated contact in the bearing test rig. Nonetheless, the aim to characterise possible layers on the surface may well be reached.

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