Development of sintered bearings with minimal friction losses and maximum life time using infiltrated liquid crystalline lubricants

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Abstract

Sintered bearings are widely used as machine elements due to their low costs in combination with a stable tribological performance. Given the current and future challenge of global conservation of energy and reliability of mechanically systems, the increase of energy efficiency of sintered bearings would have strong effect due to the tremendous number of mechanical devices. The approach of this investigation is to develop a complete system consisting of a lubricant, which is adapted for an optimized sliding bearing. Friction tests with a rotating ball-on-3-plates tribometer (μ ~ 0.005) and an application oriented component test (μ ~ 0.01) show that extremely low friction values can be realized using a liquid-crystalline lubricant in contrast to standard oils.

Keywords

Sintered iron bearings; ultralow friction; computer tomography; in-situ wear measurement

1. Introduction

Friction and wear occur in almost all engineering systems and cause energy losses and consequently high costs [1], [2], [3], [4], [5]. Improving energy efficiency of mechanical systems is one of the key factors to reduce the energy consumption and thus the global carbon emissions despite an increasing demand for energy. It has been estimated that approximately 11 percent of the annual total energy consumption for turbomachinery, transportation, power generation and industrial processes can be economized with tribological optimization [6].
To realize long-life stable and energy efficient technical systems, friction and wear can be reduced by developing novel lubrication systems. These efforts to reduce friction losses and simultaneously regarding the ecological balance can be summarized in the topics ‘sustainable’ or ‘green’ tribology [7]. Due to the minimization and increase of energy density in tribological systems the requirements for lubricants increase. For technical applications lubricants are additivated with special surface active substances (friction modifiers, extreme pressure additives) to improve the tribological performance [8], [9], [10]. But especially in terms of energy efficiency, standard lubricants on mineral oil basis and even synthetic oils have a limited potential to significantly reduce friction and wear. Therefore novel approaches for efficient lubrication are being developed on the basis of complex fluids like mesogenic fluids (MFs) or ionic liquids (ILs) [11], [12], [13], [14], [15], [16], [17], [18], [19].
This work focuses on the development of new lubricants on the basis of complex fluids with specific physical and chemical properties [20], [21]. The aim of this work was to realize ultralow friction in a technical system consisting of sintered iron bearings in combination with a specific adapted MF.
In the scientific literature monomeric liquid crystals (MLCs) have been studied for more than two decades to explore their tribological properties. At the present time there is a variety of publications, conference papers, books and patents on this issue. A summary of the current state of research on liquid crystals for tribological applications is given from Carrión et al. [22]. The proceedings of the symposium "Tribology and the liquid-crystalline state" (Washington, 1990) published by G. Biresaw [23] highlight previous research on liquid crystals in tribology and their possible application in bearings which operate in the elastohydrodynamic range [20]. This application was identified for liquid crystals (LCs) because of their high loading capacity despite low viscosity. LCs can also be used as additives in lubricants to improve the tribological behavior [24], [25], [26]. In these papers it is shown that polar groups of the LCs interact with the surface of the testing specimens and build a tribo-layer in which the alkyl chains are orientated in direction of the motion of counter surface. For tribological systems which are lubricated with LCs the influence of shear and confinement due

to the orientation of the molecules plays an important role because it influences the viscosity [27]. Figure 1a illustrates the three possible alignments of LC molecules under shear. The corresponding viscosity values are called Miesowicz viscosity coefficients [20], [28], [29]. For the nematic fluid N-(4-Methoxybenzylidene)-4-butylaniline (MBBA) η_1 shows the highest viscosity and η_2 the lowest viscosity ($\eta_1 > \eta_3 > \eta_2$) [30]. The internal friction of parallel oriented elongated molecules (η_2) along the flow direction is smaller than the internal friction of randomly oriented molecules of the isotropic liquid. Jakli et al. [31] showed that a large-scale smectic monodomain can be induced due to shear. In-lubro investigations of the orientation of molecules in tribological contacts were made from Mori et al. [32] which have measured the orientation of liquid crystals in a tribological contact using IR-spectroscopy. Analyses to shear and pressure induced liquid crystalline orientations were performed using an X-ray surface force apparatus (XSFA) [33], [34], [35], [36], [37], [38], [39], [40]. Noirez et al. [41] investigated by using neutron scattering method the orientation of a thermotropic LC at high pressure. Pikina [42] showed that shear increases the orientation long-range order of LC molecules and pressure the positional long-range order. According to these results Kumacheva [43] detected lower friction values at a higher degree of orientation. The results of these publications concerning orientation under mechanical shear show that the tribological and rheological characteristics strongly depend on the orientation of the molecules.

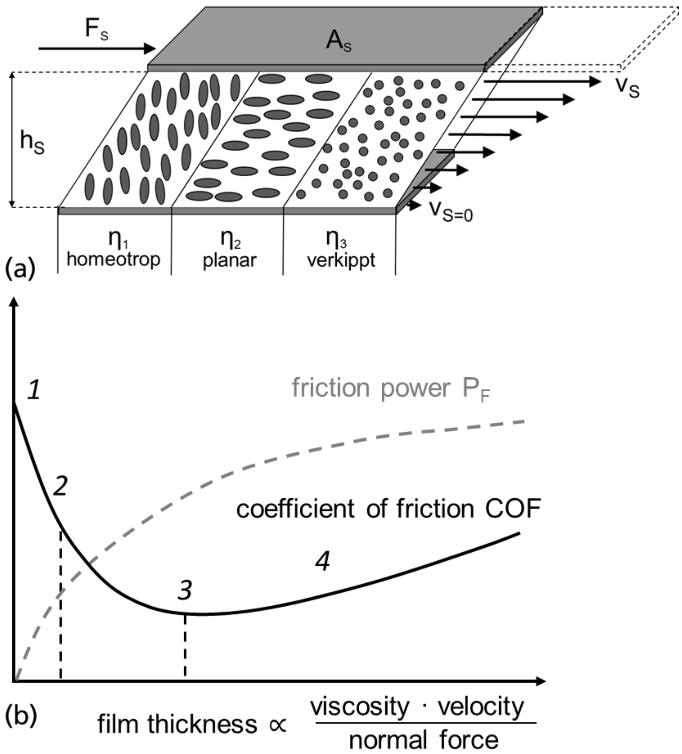


Figure 1: (a) Schematic illustration of the three Miesowicz viscosity coefficients of a liquid crystals aligned in a shear gap [20], [28], [29]; (b) Stribeck-curve with the different lubrication regimes: 1) boundary-, 2) mixed-, 3) thin-film- and 4) fluid-film-lubrication [44], [45]

For the friction and wear behavior of bearings, nanoscale processes that take place directly at the interface between bearing surface and lubricant play a crucial role. Xiang-Jun et al. [45] showed that the observable minimum coefficient of friction (COF) and the low-COF region typically appears in the thin-film lubrication regime (TFL) of the Stribeck-curve (Figure 1b). In addition, they mentioned that the confinement changes the viscosity. The confinement can also lead to a phase transition from liquid to solid. Therefore they concluded that the low COF in the TFL regime results from the orientation of molecules at confinement. A study on the transition between elastohydrodynamic lubrication (EHL) and TFL was done by Luo et al. [46] using a relative optical interference intensity technique. The presented physical model consists of three kinds of film (dynamic film, ordered lubricant film, adsorbed or static film) in the friction gap, which are constructing the TFL regime [46]. In addition, it is shown that the initial viscosity of lubricant influences the critical film thickness at which EHL changes to TFL. Jabbarzadeh et al. [47] calculated the viscosity for a six-layer dodecane film at very high shear rates (10^{11} s^{-1}) and discovered that the shear stress and film thickness abruptly decreases which is due to a nematic-like alignment of the molecules. In another publication Jabbarzadeh et al. [48] calculated that a shearing aligned six-layer dodecane film has a much lower viscosity than bulk dodecane at high shear rate (10^9 s^{-1}) which leads to low friction values at thin film lubrication.
Own preliminary work showed that specific liquid crystal fluids, tested in different tribological systems under a broad range of stresses, showed very low friction values ($\mu \sim 0.005$) and lowest wear rates. Particular MFs, respectively similar shape anisotropic fluids (1,3-diketones), were selected because of their anisotropic physical properties (e.g. viscosi-

ty, alignment of molecules). Li et al. [17] found that this ultralow friction value is induced by a novel tribochemical reaction on steel surfaces. Walter et al. [49] investigated this tribochemical reaction using infrared spectra and optical spectra of the 1,3-diketones and their complexes with iron using density functional theory simulations. Zhaohui et al. [50] analyzed the complex formation of 1,3-diketones by temperature-dependent FTIR-spectroscopy. They showed that 1,3-diketones are strong complexing agents and that the chemical structure strongly affects the liquid crystalline character of metallomesogens. Besides contact pressure temperature was found to be an important parameter for realization of ultralow friction using these fluids [13], [18]. The reduced viscosity at higher temperature leads to mixed lubrication in the beginning of the tribological tests. The consequence is a much faster formation of the metal complex and a faster decrease of the coefficient of friction.

Porous bearings are produced by sintering of metallic powder under high pressure and high temperature. Between the melted particles capillary channels remain after the sinter process. The volume of open porosity (5-30%) is filled by the lubricant (inner oil depot). Depending on the amount of porosity, life-time lubrication can be realized. This is an approximately 10-fold greater oil volume than at massive bearings. There, the lubricant supply is limited by the bearing gap volume. But due to the porosity and the capillary channels sintered bearings are less stable and sensitive to cracks. Sintered bronze is the most common material, but also sintered iron is widely used. The composition and porosity of the sinter material varies within a broad range according to the required properties. Essential elements for tribological optimization of the sintered material are: carbon, aluminum and copper.

The approach of this work is to analyze the tribological properties of a mesogenic fluid and different solid and sintered materials using component near model friction tests. These preliminary tests were carried out to understand the mechanisms which lead to ultralow friction. These findings are the basis to identify a sintered bearing system, which will be investigated using an application oriented test. With this tribological test the functionality of the sintered bearing system can be demonstrated.

2. Experimental

This study focuses on the tribological behavior of a modified MF in comparison with a standard lubricant. The pure MF-02/06 was synthesized by Nematel GmbH. Due to its chemical structure MF-02/06 shows a keto-enol tautomerism. At equilibrium state the enol form is favoured (90 %) in contrast to the keto form (10 %) at room-temperature (Figure 2). The melting point of this fluid was reduced from 5 °C to -15 °C by the application of a complex mixture of different variations of the basic MF-02/06 which is called M1231. Preliminary friction tests showed that the MF-02/06 shows very good tribological behavior using steel 100Cr6, due to its interaction with nascent iron atoms and the formation of metal chelate complexes [17]. The tribological performance of MF-02/06 (7 mPa·s at 40 °C) is compared with the mineral based oil Optigear32 (Castrol, 29 mPa·s at 40 °C) using the solid 100Cr6 material. This oil was used because of its comparable viscosity, area of application and denoted advantages (long-term and life-time lubrication, reduction of the coefficient of friction, reduced energy, maintenance and disposal costs [51]). For the sintered materials a commercial available semi-synthetic oil based on esters and hydrocarbons with additives (reference oil, 50 mPa·s at 40 °C) was used as refernece oil because this oil is used in different technical applications containing sintered slide bearings (e.g. in watches).

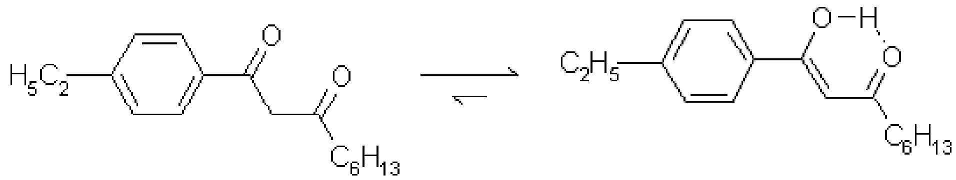


Figure 2: Chemical structure of the mesogenic fluid MF-02/06 and its keto-enol tautomerism

The tribological tests were divided in model friction tests and application oriented component tests. Model friction tests were carried out to analyze the tribological behavior of MF-02/06 at different load spectrum, especially the influence of the initial contact pressure on friction and wear. In-situ temperature measurements during a friction test using a 2.5mm radial bearing showed that the temperature increases up to 100 °C with a standard oil. Therefore the model tribotests were performed at 90 °C and 100 °C and using two different test geometries (Figure 3a, b):

- Reciprocating cylinder-on-disk geometry; Optimol Instruments SRV tribometer, solid 100Cr6 samples, test parameters: 50 N; 1 mm; 50 Hz; 90 °C; 130 MPa
- Rotating ball-on-3-plates geometry; Anton Paar MCR501 rheometer using tribological measuring cell; solid and sintered materials; test parameters: 20 N (255 MPa) and 10 N (128 MPa) at different velocities
- Rotating shaft-bearing geometry (innerØ2.5 mm); test parameters:35 N; 45 MPa; 0-200 mm/s; RT; test procedure: successively one cycle left and right; 1000 cycles per direction of rotation; 5 sec waiting time after each cycle; mean value of both directions is used for analysis

Radial sinter bearings were chosen as possible and promising technical application. Therefore component tests were performed with a rotating shaft-bearing geometry (Figure 3c). Using this test setup the resulting wear was measured in-situ with a laser beam, which determines the changing position of the bearing due. These tests were conducted using the optimized and for iron bearings adapted mesogenic fluid mixture (M1231):

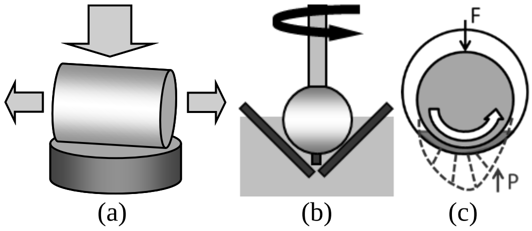


Figure 3: Geometry of model friction tests: (a) reciprocating cylinder-disk; (b) rotating ball-on-3-plates; (c) radial bearing

Model friction tests were carried out using solid 100Cr6 material (Table 1), because the most preliminary results are based on this material.

Table 1: Material characteristics of the solid materials

Solid steel 100Cr6	cylinder	disk	plate	ball
Ra (µm)	0.07	0.05	0.20	0.03
Rz (µm)	0.60	0.46	1.43	0.13
HRC	62	62	23	60
density (g/cm³)		7.8		
dimension (mm)	15x22	24.0x7.8	6x15x3	Ø6.35

In addition, to identify the influence of the material composition and characteristics different sintered materials were tested (Table 2). These specific sintered materials were chosen due to their similarity to steel 100Cr6. The amount of wear volume was measured using white light interferometry. A further analysis was carried out with the IR-spectrometer to verify chemical reactions within the friction test in the lubricant.

Table 2: Chemical composition and material characteristics of the sintered materials produced by SL Gleitlagertechnik GmbH

Sintered plates	Sint100Cr6	SintA10	SintFe87	Sint100Cr6Al
Fe (%)	96.5	97.7	89.0	94.50
Cr (%)	1.5	-	-	1.50
Mn (%)	0.4	-	-	0.35
Mo (%)	0.1	-	2.0	0.10
Cu (%)	0.3	2.0	-	0.30
C (%)	1.0	0.30	-	1.00
Si (%)	0.3	-	-	0.25
Al (%)	0.1	-	-	2.00
Ni (%)	-	-	9.0	-
pore volume	10	25	10	10
Ra (µm)	1.8	0.9	0.7	6.2
Rz (µm)	16.6	12.2	7.4	41.5
HV10	66	61	198	54
density (g/cm³)	6.9	5.6-6.0	7.1	6.6
dimension (mm)		6x15x3		

The application oriented component tests were carried out at Dr. Tillwich GmbH Werner Stehr using sintered 100Cr6 and 100Cr6Al sliding bearings from SL Gleitlagertechnik GmbH. The sintered bearings have an inner diameter of 2.5 mm and an outer diameter of 7.0 mm with a width of 5.0 mm. The used 100Cr6 shaft has a diameter of 2.497 mm. The sintered bearings were immersed with the lubricant M1231 in a glass container under vacuum for 1 hour. Figure 4 illustrates the used sintered iron bearing on the basis of different visualization techniques. The pore- and surface-volume was analyzed using computer tomography (Table 3; Co. CT-Vision). As can be seen in Figure 4d the pores are well distributed in the whole bearing.

Table 3: Characteristics of the sintered slide bearing using computer tomography

Sintered bearings	100Cr6	100Cr6Al
pore volume (mm³)	9.6	14.0
pore volume (%)	5.8	8.2
number of pores	98,926	148,765
minimum (mm³)	5.22E-06	5.22E-06
maximum (mm³)	0.0142	0.0453
50th percentile (mm³)	2.61E-05	5.22E-06
pore surface (mm²)	1440.5	1458.0

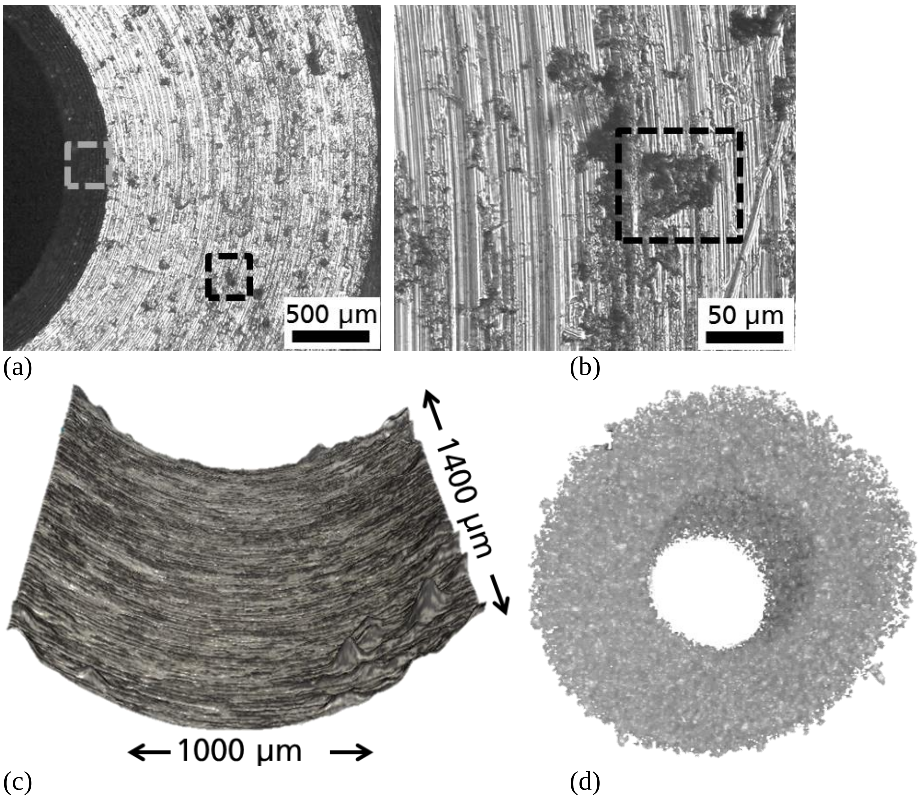


Figure 4: 100Cr6 sintered bearing before tribological testing (innerØ 2.5 mm): a), b) Analysis of frontal area using digital light-optical microscope (pore: 35 x 45 µm); c) Analysis of the friction surface of the bearing using laser scanning microscope; d) Analysis of the pore volume using computer tomography

3. Results and Discussion

3.1 Solid material

Friction tests using cylinder-disk geometry with MF-02/06 as lubricant showed an ultralow coefficient of friction (COF) of ~ 0.005 after a running-in time of nearly 6 hours in contrast to Optigear32 (Figure 5). As analyzed in preliminary work this behavior is caused by three different factors:

- Geometrical adjustment of the testing specimens accompanied with a decrease of contact pressure to approximately 10 MPa due to wear
- Chemical reaction of the 1,3-Diketones with nascent iron atoms to form a tribological active metal chalet complex
- Specific orientation of the rod-shaped molecules due to shear and pressure

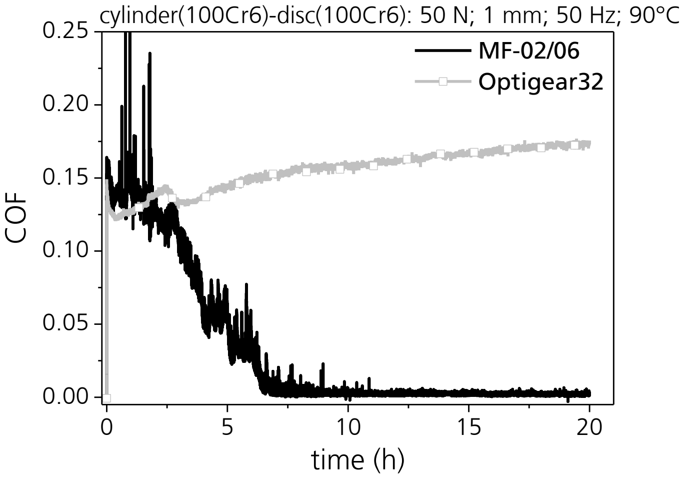
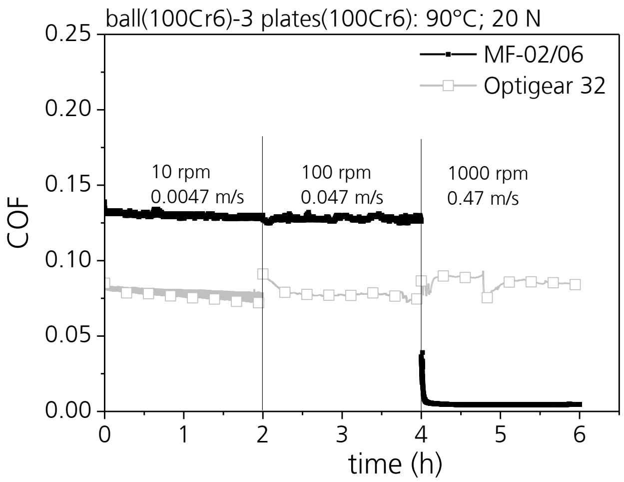


Figure 5: Reciprocating cylinder-on-disk friction tests using MF-02/06 and Optigear 32 as lubricant (100Cr6; 50 N; 1 mm; 50 Hz; 90 °C) [11]

On this basis further tribological tests with rotating ball-on-3-plates geometry were performed to analyze the behavior of MF-02/06 in contrast to reference oil at higher initial contact pressure. Friction tests with modified velocity were carried out to investigate if also ultralow friction can be reached. Figure 6a shows that using MF-02/06 at 0.47 m/s a COF of ~ 0.005 can be realized. In contrast Optigear32 shows a constant COF of ~ 0.08 at the tested three velocities. Friction tests with constant parameters over 15 at 0.47 m/s show the same and stable COF for MF-02/06 and Optigear32 (Figure 6b). In addition, due to the chemical reaction of MF-02/06 to an iron-tris-1,3-diketonat complex, a friction test was performed with the used MF-02/06 fluid. As already described this complex formation leads to an increase of viscosity [12]. Therefore the used fluid shows a totally different friction behavior and the COF didn't decrease to the ultralow values (T2, Figure 6b, COF ~ 0.05). As can be seen in Figure 6c the wear scar on the plate differs very strongly between the three fluids. In contrast to MF-02/06, with a worn area of 0.359 mm², the used MF-02/06 has with 0.057 mm² a 6-time lower amount of wear. The lowest amount of wear is realized using Optigear32 with 0.043 mm².



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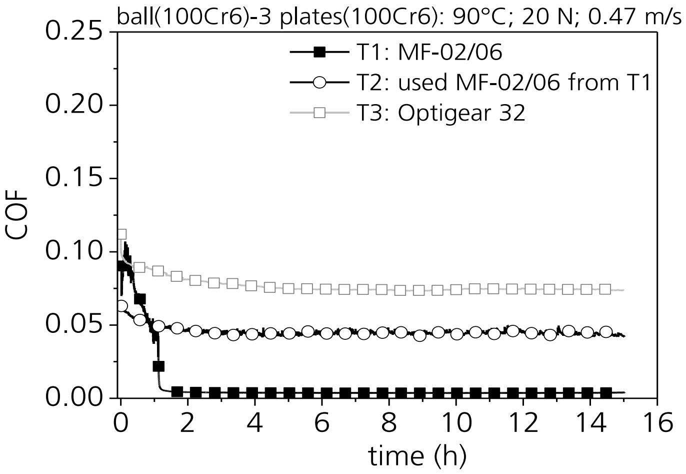

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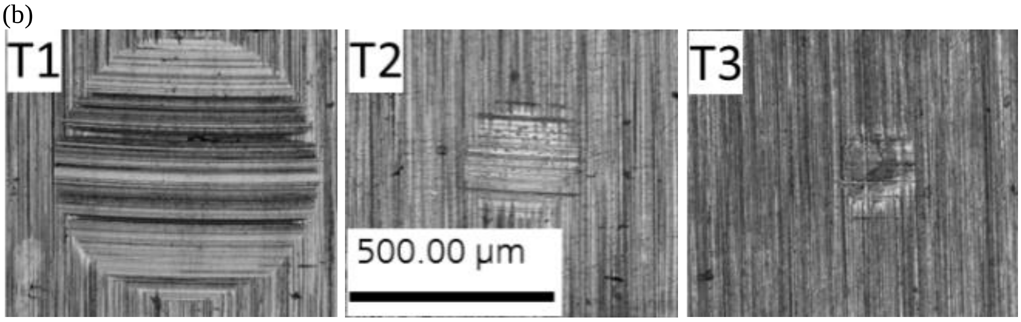


(c)

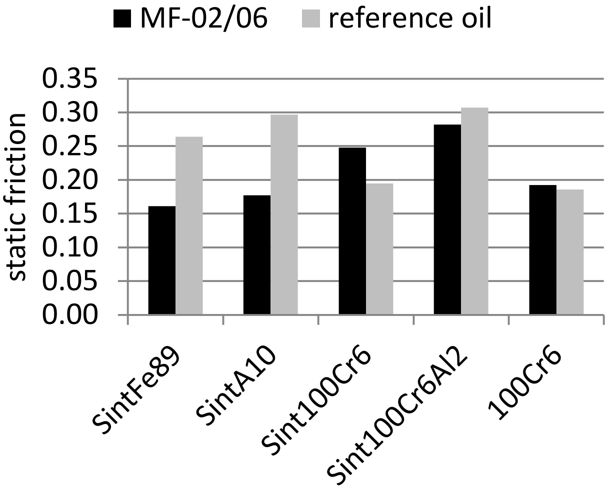
Figure 6: Rotating ball-on-3-plates friction tests using MF-02/06 and Optigear32 as lubricant (100Cr6; 20 N; 90 °C): (a) three 2 h speed steps of 0.0047, 0.047 and 0.47 m/s; (b) 15 h constant velocity of 0.47 m/s; (c) Images of the wear scar on a plate after tribological test

3.2 Sintered material

Three different sintered materials were tested and compared with solid 100Cr6. First so called multi-tribotests were performed to measure the static friction and the Stribeck behavior. The multi-tribotest consist of 4 sequences: 5 static friction measurements; 3 h conditioning at constant parameters; 5 static friction measurements; 3 h conditioning; 5 Stribeck-curves.

The mean values of the first 5 static friction values are illustrated in Figure 7a. It is noticeable that sintered and solid 100Cr6 show slightly higher static friction using MF-02/06 than with reference oil. In contrast, in combination with SintA10, Sint100Cr6Al and SintFe89 MF-02/06 reach lower static friction.

Figure 7b shows the Stribeck-curves with MF-02/06. Using SintA10 (~ 0.01) and solid 100Cr6 (~ 0.005) the COF decreases to very low values at higher speeds. The decrease of the friction value is not so pronounced at SintFe89 and Sint100Cr6. In contrast, a nearly constant COF is measured using reference oil in combination with the sintered materials with the exception of Sint100Cr6 and solid 100Cr6 (Figure 7c).



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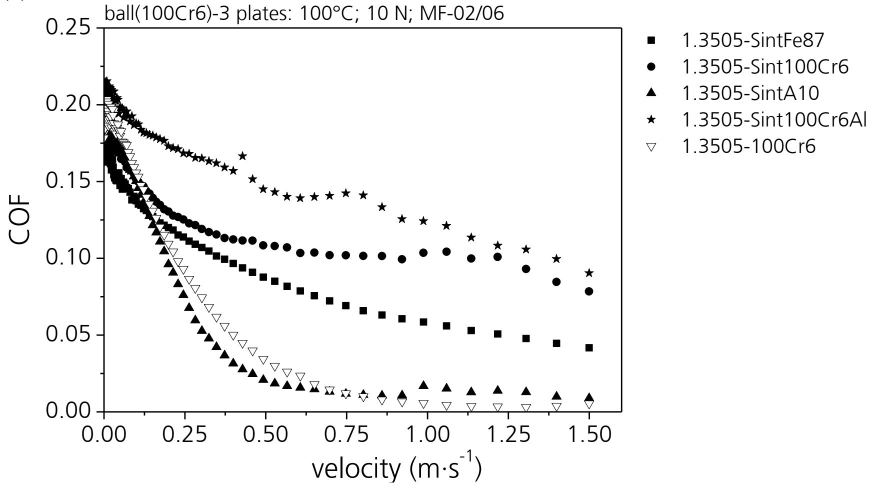

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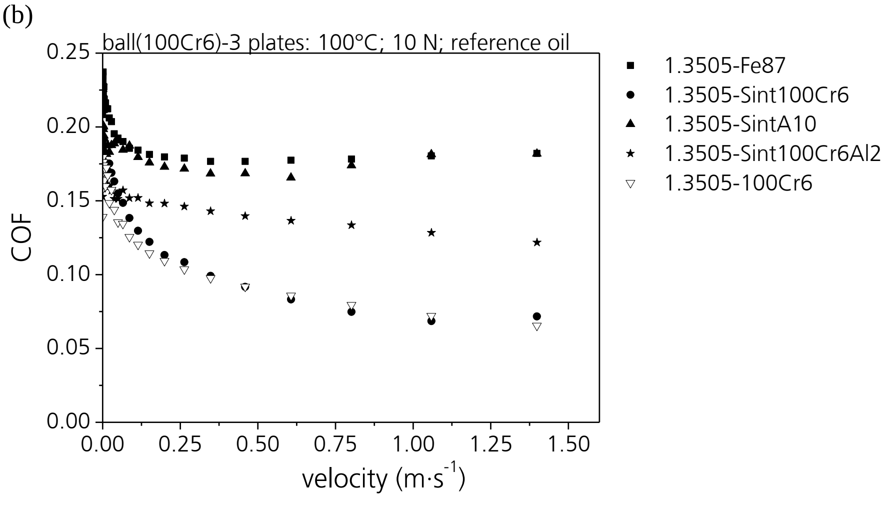
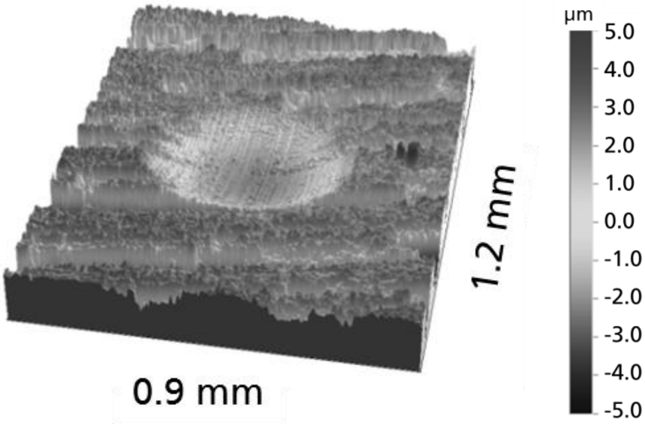


(c)

Figure 7: Results of multi-tribotest with rotating ball-on-3-plates geometry using different sintered materials (100Cr6; 10 N; 100 °C): (a) Overview of the static friction values of MF-02/06 and reference oil using rotating ball-on-3-plates geometry; (b) Stribeck-curves (0-0.47 m/s) using MF-02/06; (c) Stribeck-curves (0-0.47 m/s) using reference oil

The volume of the wear scar on the plates was measured using white light interferometer (Figure 8a). Figure 8b illustrates the amount of wear after the multi-tribotest. With the exception of SintFe89, the use of reference oil leads to a clearly lower wear volume. The wear volume using Sint100Cr6Al couldn't be measured because the wear volume was in the range of the surface roughness.



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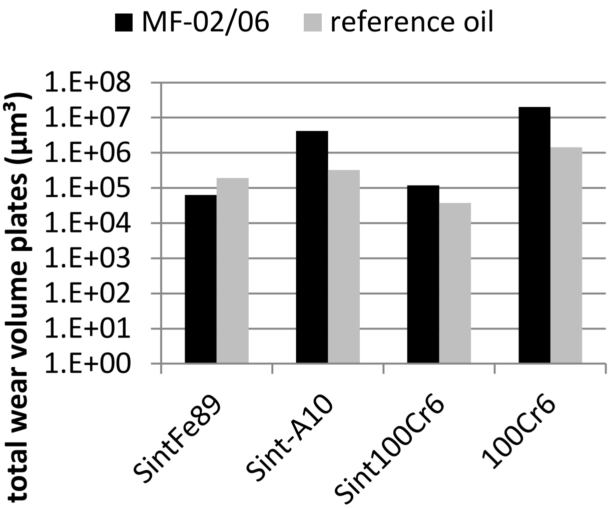
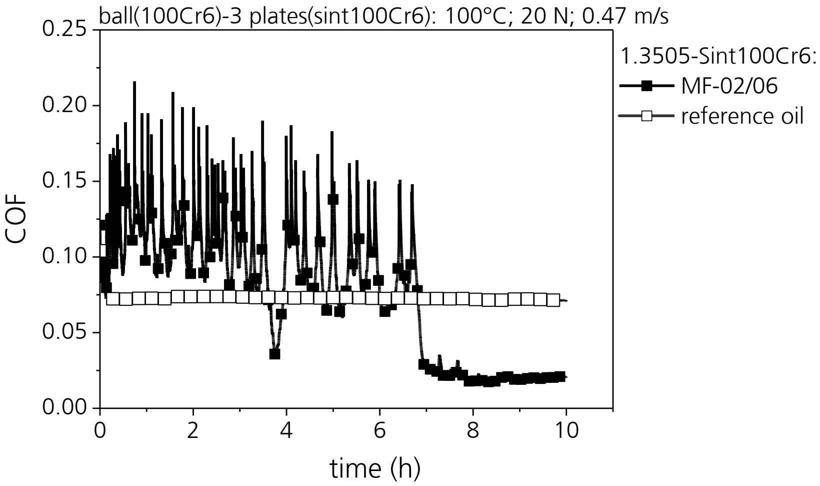


(b)

Figure 8: Wear analysis after multi-tribotest: (a) Illustration of wear scar on plate using white light interferometer; (b) Comparison of the wear volume of the three plates

Figure 9a shows exemplary the friction value of sintered 100Cr6 lubricated with MF-02/06 and reference oil with constant test parameters. Sint100Cr6 has a scattered COF during the 7 h running-in time. Lubrication with reference oil leads to an obvious higher COF. The friction values of all tested materials after 10 h testing time are illustrated in Figure 9b. In combination with MF-02/06 sintered and solid 100Cr6 reach the same minimal COF of ~ 0.02. MF-02/06 reaches lower COF as the reference oil with the exception of Sint100Cr6Al. The resulting wear volumes are listed in Figure 9c. As already measured after the multi-tribotests these tests also show that Reference oil produces clearly lower wear.



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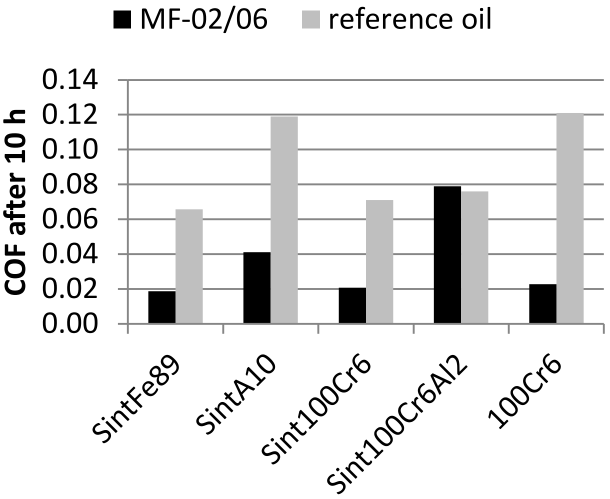

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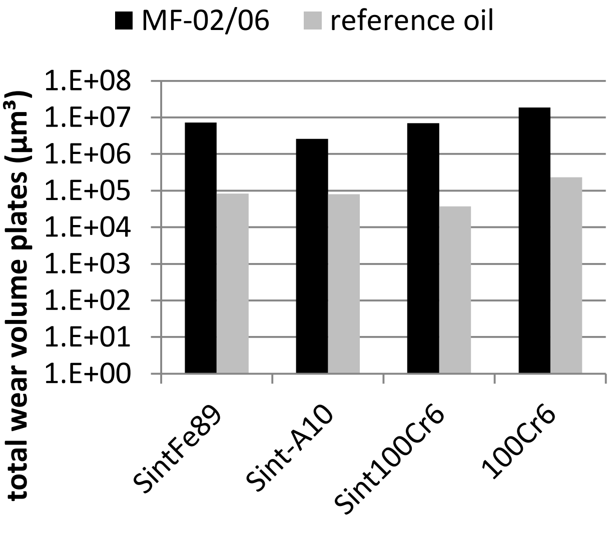

(c)

Figure 9: Friction tests with rotating ball-on-3-plates geometry at constant parameters (20 N; 0.47 m/s; 100 °C) using different sintered materials: (a) Friction diagram for sintered 100Cr6 using MF-02/06 and Reference oil as lubricant; (b) Comparison of the coefficient of friction after 10 h; (c) Wear volume of the three plates after 10 h friction test

The results of the model tribotests suggested Sint100Cr6 (low coefficient of friction) and Sint100Cr6Al (low amount of wear) as promising materials. Therefore the sintered bearings for the application oriented tests were made of these two materials. The reference oil shows nearly the same static friction value of approximately 0.13 after 2000 cycles with the same trend as M1231 using the sintered 100Cr6 bearing (Figure 10a, c). But M1231 yields a noticeably lower COF (~ 0.01) than the reference oil (~ 0.05) at sliding friction with a faster decrease of the COF. In combination with the sintered 100Cr6Al bearing the use of M1231 not only leads to a lower static friction (~ 0.13 / 0.16) but also to a lower sliding friction (~ 0.01 / 0.10) than the reference oil (Figure 10b, d). During the radial bearing tests the wear was directly measured and the resulting contact pressure calculated. During the first 50 cycles there is a fast increase of wear at all tested bearing combinations which is connected with the adjustment of the bearing and the shaft. This running-in behavior can also be seen in the decreasing COF with increasing amount of cycles. As can be seen in Figure 11a, b, the reference oil shows a comparable wear with sintered 100Cr6 (10 µm) and 100Cr6Al (13 µm). In contrast to the reference oil the use of M1231 leads to a different wear behavior. In combination with 100Cr6 a clearly higher wear (20 µm) was measured than with 100Cr6Al (12 µm), which is the same value as with the reference oil (Figure 11c, d). Due to the amount of wear the resulting contact pressures for all four tested bearings are in the range from 20 to 30 MPa (Figure 11).

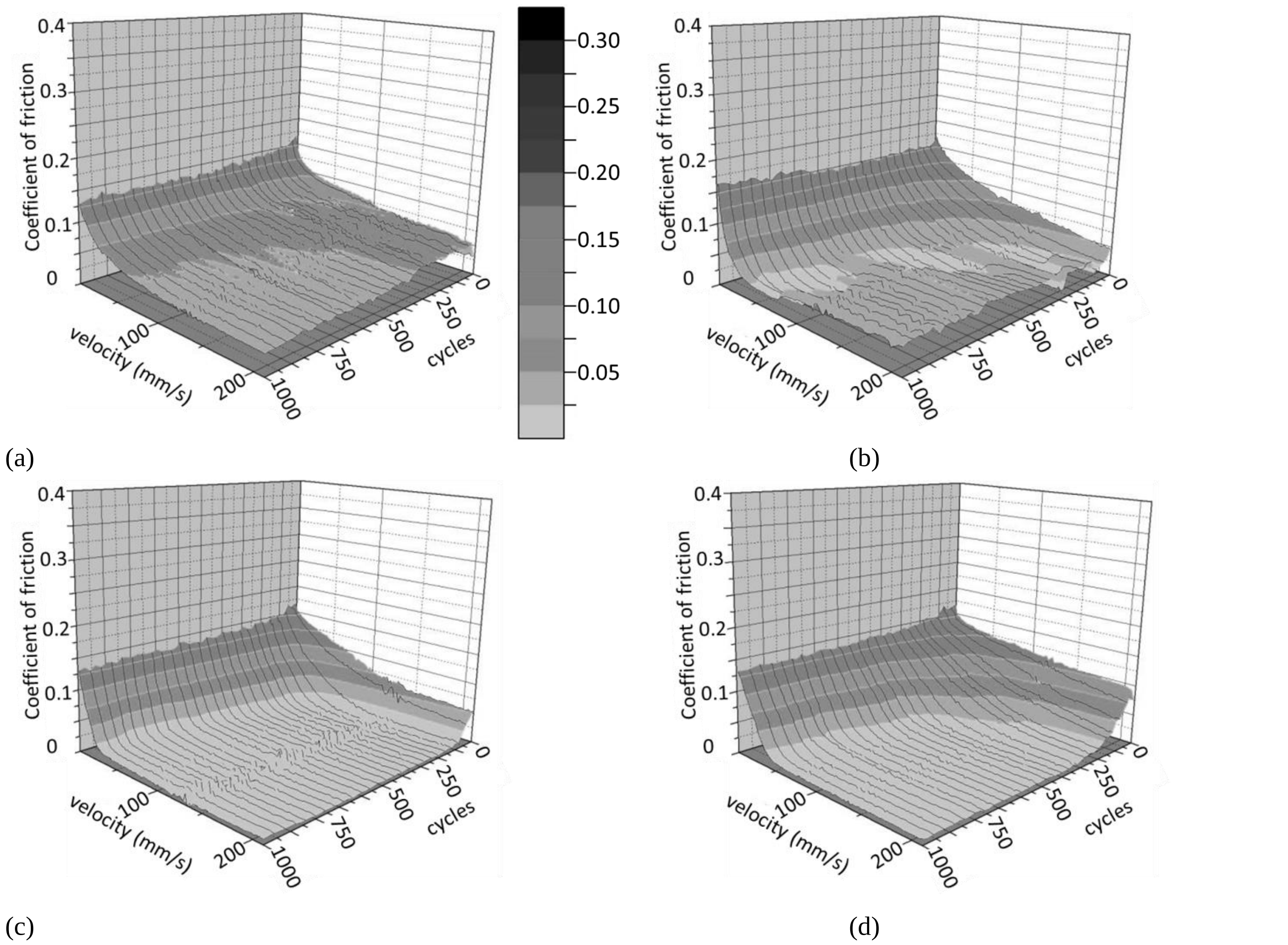

Figure 10: Friction tests using radial sintered iron bearings lubricated with the reference oil and the modified M1231 (ø2.5 mm; 35 N; RT): a) Reference oil using sintered 100Cr6; b) Reference oil using sintered 100Cr6Al; c) M1231 using sintered 100Cr6; d) M1231 using sintered 100Cr6Al

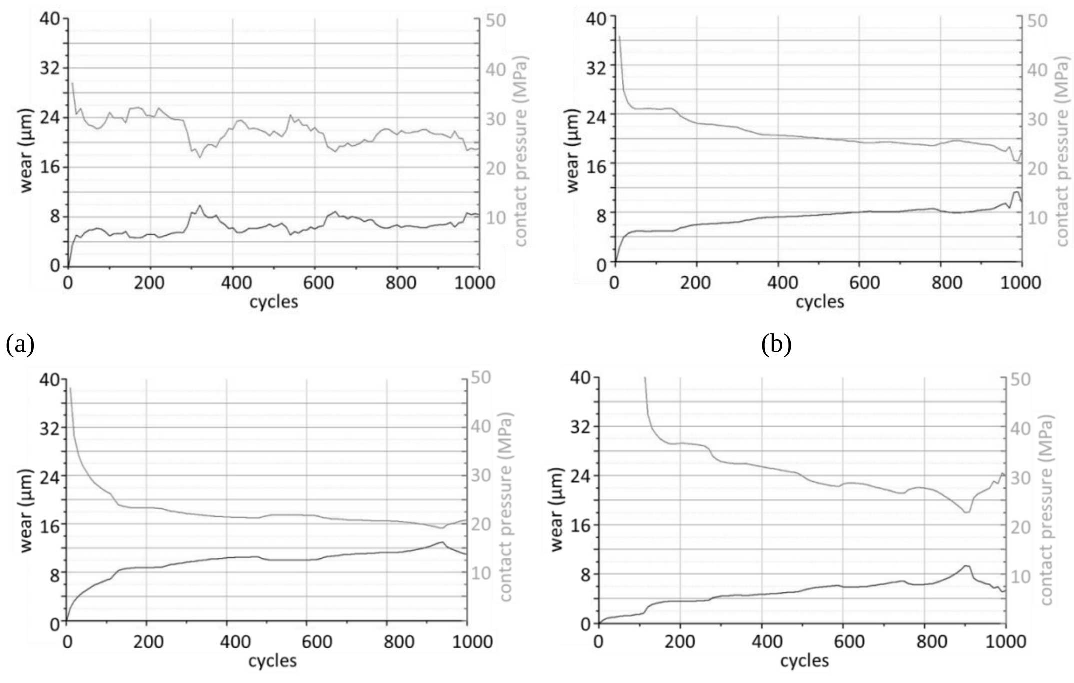

Figure 11: In-situ wear analysis using radial sintered iron bearings lubricated with the reference oil Reference oil and the modified M1231 (ø2.5 mm; 35 N; RT): a) Reference oil using sintered 100Cr6; b) Reference oil using sintered 100Cr6Al; c) M1231 using sintered 100Cr6; d) M1231 using sintered 100Cr6Al

As already measured at the model tribotests sintered 100Cr6Al shows also lower wear at the radial bearing tests than 100Cr6. But at initial low contact pressure (45 MPa) this combination also leads to ultralow friction. This different tribological behavior of sintered 100Cr6 and 100Cr6Al lubricated with M1231 may be connected to the higher amount of pores of the sintered 100Cr6Al bearings. But the plates of these two materials had the same porosity at the model tribotests. Therefore it can be assumed that the alumina content supports or leads to a beneficial chemical reaction during the friction. IR-analysis of MF-02/06 before and after friction test with Sint100Cr6 and Sint100Cr6Al is shown in Figure 12. The C=O band at 1681 cm^{-1} characterizes the amount of the keto-form and the stretching vibration at 1609 cm-1 the enol-form (Table 4). The decreasing intensity of the C=O stretching vibration and the additional appearance of the bands at 1540, 1520 and 1385 cm^{-1} after the tribotest indicate the chemical reaction of nascent iron ions with MF-02/06 to a metal-chelate complex [17], [49]. But as can be seen in particular at the intensity of the O-H stretching vibration, the triboreaction of the fluid is pronounced differently. In case of the ball-on-3-plates friction test using Sint100Cr6 in combination with MF-02/06 there is a much lower amount of complex formation in correlation to Sint100Cr6Al and with solid 100Cr6. This result is in good correlation with preliminary results because the complex formation leads to a higher viscosity and a tribo-active layer on the surface which prevents wear [12], [17]. Due to these results it can be assumed that using the alumina containing material a faster complex formations occurs which causes a lower wear rate. Therefore the initially high contact pressure (ball-on-3-plates geometry, 255 MPa) does not decrease to a value at which the molecules can orient themselves (10-15 MPa) and form ultralow friction. In contrast at already low initial contact pressure (radial-bearing test) the fast complex formation does not inhibit the development of ultralow friction but also leads to a reduction of wear. Both alumina and iron have an oxidation state of +3 which indicates the possibility for alumina also to react with MF-02/06 to a metal-chelate complex. Due to the smaller atomic size of alumina it can be assumed that this reaction runs faster than with iron, but because of the relative low amount of alumina the main reaction has to be with iron.

Table 4: IR-bands of the molecular bonds

bond	wavenumber (cm^{-1})
C=O stretching vibration	1681, 1721
O-H stretching vibration	1609
C-O stretching vibration	1540, 1520, 1385

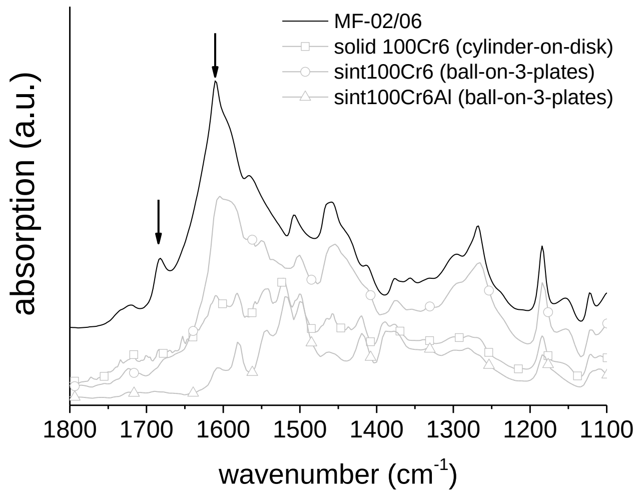

Figure 12: IR-spectroscopy of new and used MF-02/06 after friction test with solid 100Cr6 (cylinder-on-disk test, Figure 5), Sint100Cr6 and Sint100Cr6Al (ball-on-3-plates test, Figure 9)

5. Summary and Conclusions

In this investigation the tribological behavior of a pure and modified mesogenic fluid (1,3-diketone) in comparison with a reference lubricant was analyzed. The influence of different material combinations on the friction and wear behavior was analyzed. In addition, we demonstrated ultralow coefficient of friction using an optimized mesogenic mixture (M1231) for a real technical application (radial bearing). Specific mechanical and chemical requirements were identified as main impact factors to realize ultralow friction, even lower than for regular hydrodynamic lubrication. The chemical reaction of the 1,3-diketones on the surface with iron leads to a formation of a wear resistant tribo-layer [17].

In addition, the orientation of the anisotropic molecules, due to the interaction of shear and pressure, is responsible to realize ultralow friction. Results of the model friction tests (ball-on-3-plates geometry) indicate that ultralow friction values can only be realized at a relatively low contact pressure (10-15 MPa). Here it must be pointed out that the contact pressure at which ultralow friction can be achieved strongly depends on the induced shear rate into the tribological system. As explained within the thin film lubrication theory, at a very thin lubrication film the orientation of the molecules causes a change of the viscosity because of the high shear strain. This mechanism was proven using molecular dynamics simulations via Gay-Berne particles with this mesogenic fluid [19]. It was found out that simply confinement has only small effect on the ordering of the molecules. Confinement and additional shear strain leads to a change of the orientation director in sliding direction and goes along with a pronounced shear thinning. Li et al. [19] also detected that the arising iron-chelate complex have no influence on the shear thinning behavior. This reduction of effective viscosity in shear direction, due to the orientation of the anisotropic shaped 1,3-diketones, causes the ultralow friction. So it can be concluded that the realization of ultralow friction using this 1,3-diketones depends on the interaction of confinement, shear rate (reduced friction) and chemical reaction on the surface (wear protection). Due to these limiting factors sintered radial bearings were identified as promising technical application and the results show the enormous potential of the used adapted mesogenic fluid to improve the energy efficiency combined with low wear. Further investigations will be conducted to identify a specific additive package to improve the oxidation and corrosion stability of this mesogenic fluid in combination with a copper free sintered bearing.

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