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Analysis of the ultralow friction behavior of a mesogenic fluid in a reciprocating contact

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ABSTRACT

Frictional contacts that are lubricated by a mesogenic fluid exhibit ultralow friction coefficients. It is assumed that these specific mesogenic fluid forms a liquid crystalline-like structure in the sliding contact that induces hydrodynamic lubrication. This effect has been reproducibly observed in a reciprocating friction system after a certain running-in period.

The aim of the present work was to study the tribological behavior of a specific mesogenic fluid in detail in contrast to standard lubricants. Tribological experiments were performed using a reciprocating cylinder-on-disc test machine. The obtained results show that ultralow friction coefficients can reproducibly be realized. Special attention was given to the chemical transformation of the mesogenic fluid during the tribological test. It is assumed that chemical and physical interactions of the mesogenic fluid with the surface of the test specimens induce a change in the rheological parameters of the mesogenic fluid and therefore, the tribological behavior is strongly affected.

A better understanding of the tribological behavior is essential for the development of efficient production routes and for the qualification of mesogenic lubricants for possible future applications.

1. Introduction

Given the current demand to increase the energy efficiency and reliability of technical systems, there is a significant need to minimize friction and wear between moving parts in tribological applications. Since their discovery in 1888 by Reinitzer, liquid crystals were subject of countless investigations [1]. The basis for the specific physical behavior of liquid crystals is their anisotropic molecular structure. Specific orientations of the liquid crystalline phases can be achieved with different surface treatments [2], by applying an electrical voltage [3] and by inducing mechanical shear and pressure [4–7].

In previously published work on the tribological behavior of mesogenic fluids (MFs), predominantly commercially available liquid crystals were used, which were in fact developed for display applications. The idea to use mesogenic fluids in tribological applications has been discussed for almost 30 years. The outcome of the growing interest in the theory and applications of MFs as lubricants was the celebration of the *Tribology and liquid crystalline state* symposium at the 198th American Chemical Society Meeting in 1990 [8]. A review of the latest developments of liquid crystalline lubricants is summarized by Carrión et al. [9]. It is noticeable that the possibility to use MFs for tribological applications is not an exceptional way to reduce friction and wear because Kupchinov et al. [10] demonstrated that the low friction of joints in living organisms results from liquid crystalline substances in the synovial fluid.

By using MFs as pure lubricants [11–15] or as additives in base oils [16–18] a reduction of friction and wear was observed. As already mentioned, these tribological studies were performed using liquid crystals, which were optimized for optical applications and did not show ultralow coefficients of friction (COF). In contrast to these findings, it has been reported that sliding contacts, which were lubricated with specific MFs can reach ultralow friction values ($\mu < 0.005$) [19–22]. The first MFs which showed ultralow COF were synthesized by Eidenschink (Nematel GmbH, Mainz, Germany). The effect of ultralow friction was then also detected in a real engineering application [23]. The mechanisms that induce ultralow friction coefficients are not clear but the findings of Noirez et al. [24] and Idziak et al. [4] showed that external pressure and shear stress induce a molecular ordering of the molecules. The rheological properties of MFs strongly depend on the orientation of the anisotropic shaped molecules [2]. As the tribological behavior is affected by the viscosity of the lubricant [25,26] it is clear that molecular orientation effects influence the friction and wear values.

So far, one economic aspect of using MFs has been the production costs. Pure MFs that have been commercialized for LC-displays are just too expensive for tribological applications. Therefore, this

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Nomenclature

MF	mesogenic fluid
LC	liquid crystal
COF	coefficient of friction μ
RCD	reciprocating cylinder-on-disc sliding geometry
XPS	X-ray photoelectron spectroscopy
w_{cy}	calculated worn area of cylinder in mm^2
R^2	coefficient of determination
η_{MF}	calculated viscosity in mPa s after friction test
x	measured content of complex in %
t	tribological testing time in hours

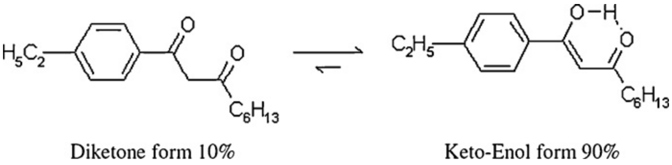

Fig. 1. Chemical structure of the mesogenic fluid 07/10 [27].

paper focuses on the research of one specific molecular class which can be much more practicable to synthesize on an industrial scale. For further optimization for possible practicability it is necessary to understand the mechanisms, which lead to ultralow friction on the molecular scale.

In this paper further tribological studies on one MF are performed to understand the mechanisms which occur during the friction test. Therefore, surface analysis, rheological and chemical analyses of the reaction products are carried out. Based on presented findings, a model is proposed on how these mechanisms lead to ultralow friction.

2. Experimental

2.1. Reagents and materials

A calamitic rod-shaped mesogenic fluid was used for the tribological tests (Fig. 1). The phenyl substituted 1,3-diketone is called 07/10 (trade name Nematel^{TM}). 07/10 was already part of different tribological studies [19–22] which illustrated the special tribological behavior of 07/10 in pure form and in mixtures over a broad range of tribological parameters.

The used test specimens are standardized for this tribological configuration (Optimol Instruments, Germany). Characteristics of the test specimens are given in Table 1. The XPS-analysis shows that there is an oxide layer on the surface and only low content of chromium is detected. 100Cr6 steel is used for rolling-element bearings, which is not a stainless steel because of the low content of chromium (1.5%).

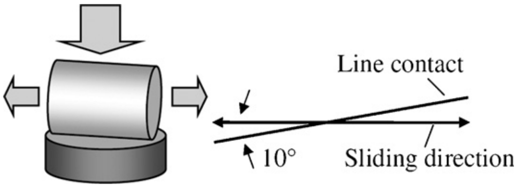

Fig. 2. Sketch of loading geometry of reciprocating cylinder on disc (RCD).

Additionally, the tribological characteristics of three standard-lubricants were tested to get comparative results. Therefore, two commercially available lubricants were used: motor oil SAE 10W-40 (Valvoline) and gear oil Optigear 32 (Castrol). Both oils are enriched with several additives such as EP-additives, sulphated ash, zinc/phosphor and calcium because they are used in specific technical applications. The third oil is an additive-free paraffin oil, which only consists of alkane hydrocarbons (Merck GmbH, Germany).

2.2. Tribological experiments

A practical tribological setup for testing lubricants is the reciprocating cylinder-on-disc test [28] (RCD, Fig. 2). This test can be used as a model test for the comparative investigation of friction and wear properties of lubricants. The typical test parameters used for the test are given in Table 2. The temperature of the testing specimen is applied by heating the disc from the seat area. Under this heating block there is a piezoelectric sensor which measures the coefficient of friction. The cylinder is inclined by 10° to the sliding direction (Fig. 2). After cleaning the samples with ethanol and acetone the lubricant was applied on the cylinder before starting the friction test. Due to the constant applied load and growing contact surface area (caused by wear) the contact pressure decreases throughout the test from initially 130 MPa.

3. Results

The results of the RCD-tests with three standard lubricants and the MF 07/10 are shown in Fig. 3. The standard lubricants show a constant and nearly similar COF of approximately 0.15 during the whole testing period. In contrast, the MF shows an ultralow COF (<0.005) after a running-in period of 7 h. During the running-in phase mixed lubrication is dominant. In this regime, wear is relatively high because of solid–solid contacts of the testing specimens [21]. This solid contact leads to stick-slip effects during the first 2 h. It must be pointed out that at the testing temperature of 90 °C the mesogenic fluid is in the isotropic phase.

After the tribological tests, wear of the cylinder and disc was analyzed. Fig. 4 shows the wear profile of the disc which was measured using a stylus profilometry. The diagram in Fig. 5 illustrates the worn volume of the cylinder and the calculated mean contact pressure after the tribological test. It can be clearly seen, that the two reference lubricants show the lowest wear on the disc (Fig. 4) and on the cylinder (Fig. 5b). The MF leads to a lower contact pres-

Table 1
Characteristics of the test specimens.

	Cylinder	Disc
Material	Steel 100Cr6	Steel 100Cr6
Diameter	15.0 mm	24.0 mm
Length, height	22.0 mm	7.9 mm
Elastic modulus	226.1 GPa	
Hardness	62.3 HRC	60.0 HRC
Surface roughness		
R_a	0.06 μm	0.07 μm
R_z	0.46 μm	0.60 μm

Table 2
Test parameters of tribological experiments.

Parameter	Value
Testing temperature	90 °C
Ambient temperature	25–30 °C
Relative humidity	20–30%
Normal load	50 N
Frequency	50 Hz
Stroke	1 mm
Initial Hertzian contact stress (line contact)	130 MPa
Duration	Varies