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Performance and mechanisms of silicate tribofilm in heavily loaded rolling/sliding non-conformal contacts

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ABSTRACT

Lubricant performance is vital as heavy-duty gear manufacturers increase power density in their efforts towards increased efficiency. In this work, a recently developed ionic liquid is introduced as a multifunction additive for use in hydrocarbon base fluid. A ball-on-disc tribological test machine was used to evaluate friction and wear in heavily loaded mixed rolling/sliding conditions. The novel multifunctional additive is benchmarked against conventional axle-gear oil additives, and results shows excellent tribological performance in terms of friction and wear. Post-test surface analysis of the wear scars revealed a silicate based tribofilm derived from the novel ionic additive, contrary to conventional phosphorous and/or sulfur based. The silicate tribofilm is correlated to a significantly increased wear resistance and vastly improved running-in performance.

1. Introduction

Currently, the transportation by trucks and busses alone is responsible for approximately 6% of the total energy consumption in the world [1], whereupon a significant amount of the fuel energy is attributed to overcome friction in moving components [2]. Hence, immediate opportunities towards a sustainable society are attainable by optimising tribological contacts for improved performance. The present transmission design strategy aims at increasing power density by developing lower weight components and by using lower viscosity lubricants for reduced churning and pumping losses [3], [4]. Such a trend drives heavy-duty gears to operate in increasingly severe lubrication regimes. The obvious outcome is increasing friction coefficients, and reduced service life, if not adequate actions in lubricant design are taken [5].

Fully formulated gear lubricants typically contain 5-20 mass percent additives (tribo-improvers, maintainers, and rheo-improvers) [6] aimed at enhancing the base oil properties. The tribo-improving additives, i.e. the friction modifying additives (FM), anti-wear (AW) and extreme pressure (EP) agents, has conventionally been used to optimise performance in the different lubrication regimes classified in Stribecks versatile lubrication model [7]. Typically, FM:s are considered to be active in the transition between elastohydrodynamic lubrication and mixed lubrication by forming easily-sheared vertically oriented adsorbed monolayers on top of the metallic surfaces [8]. AW and EP additives are generally active in more severe lubricating regimes (mixed and boundary lubrication) by adsorbing to metallic surfaces, with subsequent chemical reactions for deposition of inorganic films [9]. There is no direct consensus among researchers, but commonly these films are referred to as tribofilms, boundary films or reaction layers. Even though still evolving [10–15], the basic mechanism of AW:s typically originates from organo-phosphates that protects surfaces by forming durable tribofilms. These tribofilms function to enhance wear resistance of the upper most layers of the steel surface when exposed to severe sliding conditions with simultaneous asperity interference. EP:s, typically being sulfurized in composition [6], [16], but also commonly being chlorine or phosphorous based [17], are on the contrary to FM:s and AW:s, not used to resist wear. Instead, these are used to form sacrificial surface layers that increase seizure loads to ultimately avoid catastrophic machine failure. The above mentioned tribo-improvers represents the conventional lubricant design strategy [18].

A whole other branch of intensively investigated compounds are those known as room temperature ionic liquids (RTIL), i.e., salts composed of anions and cations, that are in the liquid state at ambient temperature. Initially, they were studied for a diverse variety of applications other than lubrication [19]. In 2001 [20] the RTIL technology was brought to the field of tribology, and in the following decade, they were intensively explored as lubricants, as indicated by the many reviews published on the topic [21–26]. RTIL:s are interesting mainly because of their, in comparison to conventional lubricants, unique physical and chemical properties; e.g. their low volatility, the ions inherent polarity for increased affinity to metallic surfaces, and

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Nomenclature

SQL	Squalane (base fluid)
h_m	Minimum lubricant film thickness [m]
AW	Antiwear agent
δ	Hertzian rigid body displacement [m]
EP	Extreme pressure agent
b	Full Hertzian contact width b = 2a [m]
P-SiSO	Ionic liquid tribo-improver highlighted in this work
a	Hertzian contact radius [m]
RTIL	Room temperature ionic liquid
R_x	Reduced radius of curvature in x direction [m]
E	Elastic modulus [GPa]
U	Dimensionless speed parameter [-]
N	Poisson's ratio [-]
G	Dimensionless material parameter [-]
H	Hardness [HRC]
W	2D dimensionless load parameter [-]
S_q	Surface roughness by root mean square average (RMS) [μm]
M	Moes dimensionless material parameter [-]
R_q	Roughness profile by root mean square average (RMS) [μm]
L	Moes dimensionless load parameter [-]
ρ	Density [g/mL]
k	Ellipticity parameter [-]
η	Viscosity [mPas]
A_d/A_i	Ratio between deformed and initial asperity heights [-]
η_0	Ambient viscosity [mPas]
Λ^*	Amplitude corrected lubrication quality parameter [-]
$\partial\eta_0/\partial T$	Temperature viscosity gradient [mPas/K]
∇_2	Dimensionless wavelength parameter for circular conjunctions [-]
α	Pressure-viscosity coefficient [GPa^{-1}]
x	Rolling direction coordinate [mm]
K	Thermal conductivity [W/mK]
y	Transverse to rolling direction coordinate [mm]
W_D	Wear depth [m]
z	Height coordinate [μm]
W_W	Wear width [m]
u_1	Velocity of ball [m/s]
W_L	Acquired wear length [m]
u_2	Velocity of disc [m/s]
$\widetilde{A}_{C-S}$	Total wear of the Hertzian cross-sectional area [m^2]
˜	Entrainment speed [m/s]
Σ	Slide to roll ratio [-]

their subsequent tribofilm forming capabilities for EP and AW protection. Great efforts have been made to utilize the beneficial effects of RTIL:s as lubricant additives [27]. A vast challenge was initially to solve the problem of their inherent low solubility (≪1%) in common non-polar hydrocarbon base oils. This was however overcome in 2012 [28], when a phosphorous based anion and cation was synthesised for increased miscibility to act as AW additive in commercially available hydrocarbon base oils. In similarity to conventional AW:s (such as ZDDP), the RTIL successfully increased wear resistance by deposition of a phosphorous based tribofilm. After that, previous economical restrictions of RTIL:s were somewhat eased [27], and they became feasible in high volume technical applications such as transmissions fluids.

Viability to large scale applications seem plausible since experimental evidence suggest that tribological properties of RTIL can be maintained even at low concentrations [29]. Hence, in the past 5 years, a significant amount of investigations has been set out to examine the possibility of RTIL:s as additive in hydrocarbon base fluids, see e.g. Refs. [28], [30–40]. Evaluations from these studies have demonstrated that RTIL:s can function to effectively reduce friction and wear when used as additive in steel-steel contacts by forming protective tribofilms. Most commonly, by incorporating the conventional tribo-improving design strategy, i.e. with phosphorous and sulfur based molecules, but also including varieties of molecules containing fluorine, boron, and nitrogen. However, the above mentioned RTIL:s have been evaluated in pure sliding BL model tests that does not represent the conditions found in heavy-duty gears. In contrast, not many investigations have been conducted to study RTIL:s under gear like conditions, i.e., highly pressurised, mixed rolling/sliding and elevated temperatures. To the best of the author's knowledge, those concerning RTIL:s as additives are [41–43], and base fluids are [44–46], Therefore, knowledge about RTIL

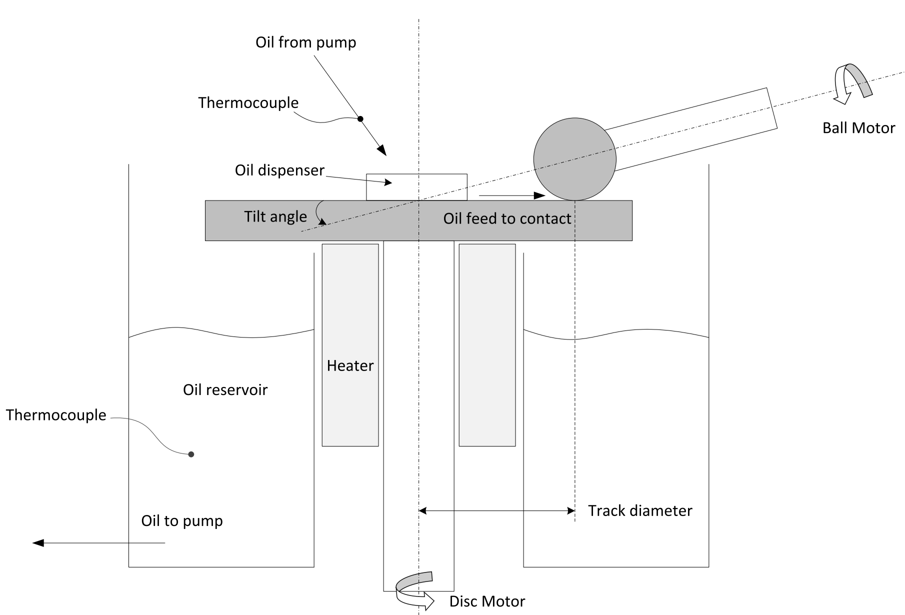

Fig. 1. Schematic illustration of the WAM 11 ball-on-disc machine showing the most essential components.