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Anti-spreading behavior of 1,3-diketone lubricating oil on steel surfaces

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ABSTRACT

For many precision devices with limited amount of lubricants, the retention of lubricating oil between solid surfaces is of great significance for the lubrication reliability in the long-term operation. In this study, the spreading behavior of a synthetic 1,3-diketone lubricant (1-(4-ethyl phenyl) nonane-1,3-dione) 02/06 on steel surfaces was investigated. By measuring the surface tension of oil and the surface energy of steel, the spreading parameter of 02/06 was determined, which was much smaller than the reference oils with similar viscosity. Rotary friction test shows that 02/06 was positioned at the contact region in the presence of a strong centrifugal force and performed a stable ultralow friction. Moreover, the addition of 02/06 into the reference oils also improved the lubricant retention.

1. Introduction

The droplet migration driven by the surface tension gradient, firstly identified in the so-called "tears of wine", is well-known as the Marangoni effect [1]. The surface tension gradient can be caused by differences in composition, concentration or temperature within the liquid. In oil lubrication system, direct asperity contacts of sliding surfaces can generate a locally much higher temperature at the contact area than surroundings [2]. This thermal gradient can induce the spread of lubricating oil from the rubbing area [3], which not only reduces the amount of fluid available for lubrication, but also accelerates the evaporation of fluid due to the increase of the exposed surface area [4]. Thus, the prevention of oil spreading or creeping is of great importance for the reliability of its lubrication performance [5].

In the case of precision lubrication [6,7], e.g. the lubrication of precision instruments, micro-engines and micro sensors, the retention of lubricating fluids is particularly significant. For large machineries, the whole bearing is usually surrounded by a viscous lubricant which is continually renewed at determined intervals of time. However, for devices on the micro- or even nanoscale, lubricants with low viscosity are often used to minimize the friction [8]; meanwhile, owing to the limitation of operating environment, the quantity of applied lubricants is very limited and the machine usually keeps running without oil replenishment for many months, years or even entire lifetime [9]; moreover, as many functional components are intensively integrated in the device, the contamination of spreading lubricants to some sensitive parts is another serious problem. Therefore, the development of precision lubrication systems brings a severe challenge to position the lubricant close to the contact and prevent it escaping.

To meet the high requirement of lubricant retention for precision lubrication, many research efforts have been devoted to investigate the lubrication system with low oil spreading [10–14]. As the spread of a liquid is strongly determined by the surface tension of the liquid and the surface energy of the solid surface [15,16], there are mainly three approaches to obstruct liquid spreading: (1) Use of a pure none-spreading liquid. W. Huang et al. [17] studied a 1-ethyl-3-methylimidazolium tetrafluoroborate ([Emim][BF4]) ionic liquid lubricant, which has much higher surface tension than silicone oil, polyalphaolefin (PAO) oil and perfluoropolyether (PFPE) oil. In contrast to the reference oils, no migration of ionic liquid droplet was observed under the same temperature gradient. (2) Addition of carefully selected solutes as additives. Q. Dai et al. [18] incorporated four different additives into diester base oil

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Nomenclature

COF	coefficient of friction
η	dynamic viscosity (mPa·s)
γ_L	total surface tension (mN/m)
γ_L^D	dispersive component of surface tension (mN/m)
γ_L^P	polar component of surface tension (mN/m)
γ_S	total surface energy (mJ/m^2)
γ_S^D	dispersive component of surface energy (mJ/m^2)
γ_S^P	polar component of surface energy (mJ/m^2)
θ	contact angle (°)
SP	spreading parameter (mJ/m^2)

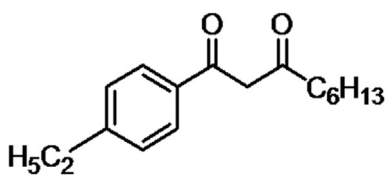

Fig. 1. Molecular structure of 1,3-diketone 02/06.

Table 1
Dynamic viscosities η of 02/06, PAO2 and 4121 at 20 °C, 40 °C and 100 °C at a shear rate of 1000 s^{-1}.

Lubricating oils	$\eta_{20\,°C}$ (mPa·s)	$\eta_{40\,°C}$ (mPa·s)	$\eta_{100\,°C}$ (mPa·s)
02/06	8.9	4.2	1.3
PAO2	7.2	3.5	1.0
4121	7.6	3.6	1.1

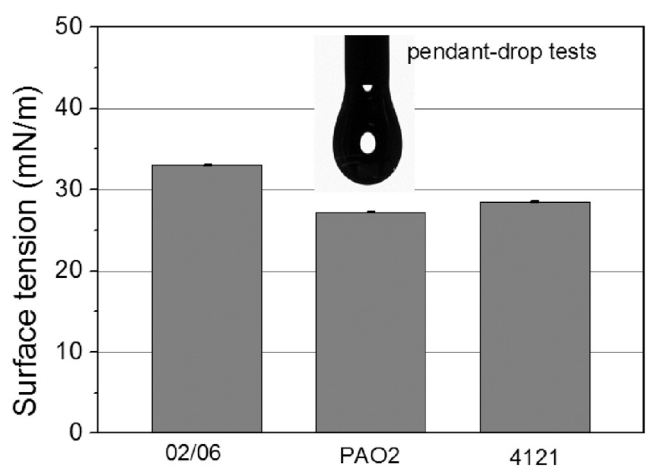

Fig. 2. Surface tensions of 02/06, PAO2 and 4121 measured by pendant-drop tests.

and investigated their surface tension coefficients and migration behavior. The result suggests that the oleic acid additive have strong affinity to the metal surface, which can extremely enhance the adsorption ability of the lubricant and slow down its migration. (3) Modification of the solid surface through chemical coating or surface texture. J. Y. Leong et al. [19] coated a monolayer of octadecyltrichlorosilane on silicon surfaces using a micro-contact printing technique. Spin tests indicate that modified surfaces can anchor 1 μl drops of hexadecane when centrifugal forces of up to 220 μN are applied. In the direction of surface texture design, Q. Dai et al. [20] fabricated micro-dimple patterns with different

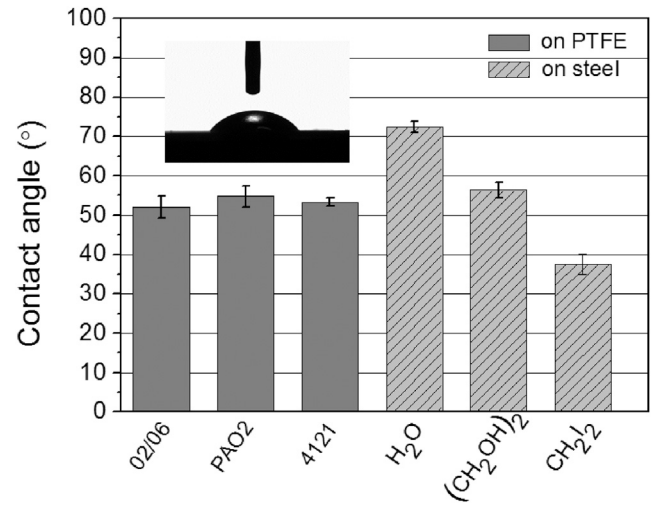

Fig. 3. Contact angles of 02/06, PAO2 and 4121 on the PTFE sheet; contact angles of deionized water, ethyleneglycol and diiodomethane on the steel disc.

Table 2
Surface tension/energy and its dispersive and polar component for the materials studied; spreading parameter of three oils on steel surfaces.

Materials	γ_L (mN/m)/ γ_S (mJ/m^2)	γ_L^D (mN/m)/ γ_S^D (mJ/m^2)	γ_L^P (mN/m)/ γ_S^P (mJ/m^2)	SP (mJ/m^2)
02/06	32.99	30.92	2.07	6.95
PAO2	27.24	19.83	7.41	11.54
4121	28.45	22.04	6.41	11.06
Steel	41.05	35.17	5.88	/

Table 3
Surface energy of unmodified steel and modified steel, and spreading parameter of 02/06 on them.

Materials	γ_S (mJ/m^2)	γ_S^D (mJ/m^2)	γ_S^P (mJ/m^2)	$SP_{02/06}$ (mJ/m^2)
Unmodified steel	41.05	35.17	5.88	6.95
Modified steel	37.34	35.38	1.96	4.20

geometric parameters on stainless steel surfaces. It is found that the deformation contact line of an advancing edge, induced by the dimple, resists the migration of paraffin oil over the dimple.

In prior work [21–23] a synthetic 1,3-diketone (1-(4-ethyl phenyl) nonane-1,3-dione) oil, abbreviated in the following as 02/06 (Fig. 1), has been studied, which shows an ultralow coefficient of friction (≈0.005) on steel surfaces. Its superlubricity is attributed to a rather complex mechanism: the tribochemical reaction between 1,3-diketone and iron eliminates asperity contacts and leads to a full fluid film; the generated iron-diketo complexes are soluble in the lubricant, which avoids the formation of wear debris; due to the strong intermolecular interaction of the lubricant, a molecular alignment could be induced by the strong shear, which lowers its effective viscosity and leads to the ultralow friction in the thin film lubrication regime. Based on its excellent lubrication performance, this low viscous diketone oil (4.2 mPa s at 40 °C) appears to be a suitable lubricant candidate especially for precision lubrication. However, aiming at the application for precision lubrication, besides the ultralow friction, the anti-spreading behavior of this 1, 3-diketone oil need further study. In the present work, the spreading parameter of 1,3-diketone oil on steel surfaces was determined through pendant-drop tests and contact angle measurements. The influence of its chemisorption on steel was also discussed. Its anti-spreading ability and lubrication reliability were analyzed using rotary friction tests.

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