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Probing carbon-based composite coatings toward high vacuum lubrication application

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ABSTRACT

For challenges in minimizing friction and wear of spatial mechanical systems, synergetic lubrication coatings were prepared by spinning liquid lubricants and hybrid greases on the diamond-like carbon (DLC) films, and were evaluated whether they could achieve a long-term safe and reliable operation under high vacuum. Under high vacuum conditions, liquid lubricants significantly reduce the friction and wear of DLC films. Hybrid greases not only show excellent lubrication performance, but also greatly enhance the tribological behavior of DLC films, especially the grease with optimal proportion. Such excellent tribological performance of DLC-based composite coatings at low applied loads depends on the synergy of DLC and fluid film, in reverse the tribo-chemical reaction film under harsh working conditions.

1. Introduction

Aerospace systems include various drive mechanisms, such as reaction wheels, gyroscopes, gears, pumps, actuators and so forth [1]. With rapid progress of aerospace devices, challenges of space lubrication have been an obstacle that limits the human exploration of the universe [2]. The space applications of these devices require low coefficient of friction (<0.1) and low wear rate ($<10^{-6}$ $mm^3N^{-1}m^{-1}$) to ensure high reliability, high precision and much long durability [3]. Taking into account these requirements under space environment, space lubrication systems not only possess self-adjusting and adaptive abilities to environment, but also provide low friction and wear [4]. Composite lubricating coatings give a positive response to the challenges of space application [5–7].

Space environment is completely different with atmospheric environment, such as ultra-high vacuum, alternate high/low temperature, high-energy particles irradiation, energetic atomic oxygen, and so forth [8,9]. Diamond-like carbon (DLC) has high mechanical hardness, excellent anti-wear, good corrosion resistance and high chemical inertness because it is metastable form of amorphous carbon with most of sp^3 bonds [10–12]. Hence, it is regarded as one of the most promising solid lubricating materials for providing high hardness and low wear through minimizing abrasion, shear and adhesion [13,14]. Kim et al. studied the effect of nano-scale surface texture on wear resistance of DLC in dry, humid and liquid water environments, found that nano-texturing significantly reduced the wear of DLC films in dry and humid nitrogen [15]. Wang et al. synthesized fluorine and sulfur co-doped amorphous carbon (a-C:S:F) films with ordered carbon structure and a-C:S:F films with 2.0 at.% H show the ultra-low steady-state friction coefficient, which mainly depends on the concentrations of S and F in the films [16]. Tagawa et al. investigated the effect of atomic oxygen beam exposure on the morphology and tribological behavior of MoS_2 and DLC film, and found that DLC surface was intensively oxidized, probably causing the dramatic decrease of lifetime, but its friction behavior has not been affected [17]. Liu et al. explored the evolution of the surface structure of DLC induced by space irradiation and the tribological performance of the composite coatings composed of DLC and lubricant under high vacuum [18]. They found that the high-energy particles irradiation changes the structure of DLC films through the sp^3-to-sp^2 bonding transformation, and the wear was obviously increased due to the irradiation-induced damage to lubricating materials. Such excessive wear causes the short travelling distances of DLC film, namely rolling or sliding cycle of less than ten million under space environment, whereas it is of paramount importance and significance for DLC film to minimize the wear and ensure a long service life.

Oil and grease as popular lubricants have been favored by derive

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Table 1
Lubricating grease composition and designation.

Designation	Lubricating grease
MACs grease	MACs grease
MACs grease + A	MACs grease + 2.0% ZDDP
MACs grease + B	MACs grease + 2.0% MoDTC
MACs grease + C	MACs grease + 0.5% ZDDP/1.5% MoDTC
MACs grease + D	MACs grease + 1.0% ZDDP/1.0% MoDTC
MACs grease + E	MACs grease + 1.5% ZDDP/0.5% MoDTC

mechanisms of spacecraft since they possess very good lubrication [19,20]. However, choosing suitable liquid lubricants for space applications is vital as the selected lubricants must overcome the influence of harsh space environment including ultra-low ambient pressure, broad temperature ranges from −120 to 150 °C and high-energy particle radiation [21]. Considering the evaporative loss, viscosity-temperature property and thermal stability of liquid lubricants, multialkylated cyclopentanes (MACs) and ionic liquids (ILs) are an appealing choice for space lubrication [22]. MACs are attracting widespread attention on potential applicability for space derive mechanisms because of the ultra-low vapor pressure, good viscosity-temperature property, high chemical and thermal stability [23,24]. ILs are composed of organic cations and organic or inorganic anions, including phosphonium, imidazolium, ammonium, and pyridinium cations, and tetrafluoroborate ($BF4^-$), hexafluorophosphate ($PF6^-$) anions and so on, which could be tailored by varying cation or anion moieties and allows them to possess a series of adjustable physicochemical properties [25,26]. And ILs have been investigated as versatile lubricants due to their negligible vapor pressure, wide temperature range, high thermal stability, and so forth [27]. For example, the excellent friction reduction and wear resistance of imidazolium based ILs composed of BF_4^- or PF_6^- anions was assigned to good physicochemical properties and tribo-chemical reaction film, because the BF_4^- or PF_6^- anions would be readily decomposed to form anti-scratch component on the friction pairs [28]. Unfortunately, it was found that liquid lubricants exist initial seizure-like high friction and can lead to high wear by high contact pressure under vacuum conditions. Given the respective characteristics of solid film and liquid lubricants, the synergy of DLC film and lubricating oil or grease will be very beneficial to space lubrication because the synergistic effect may minimize their individual shortcomings for enhancing the tribological performance. In addition, greases have been used for lubrication and seal of mechanical equipment at ground level or in vacuum, and their service life is longer than that of solid lubricants because of the replenishment and the hydrodynamic effects [29,30]. So far, reports on lubricity of low-volatile greases prepared by MACs oil are rare.

In this paper, we fabricated two lubrication systems, one is DLC-liquid composite coatings including DLC-MACs and DLC-ILs by homogeneously spun on DLC films, the other is DLC-grease with zinc dialkyldithiophosphate (ZDDP) and molybdenum dialkyldithiocarbamate (MoDTC) in different ratio composite coatings by spinning the hybrid greases on DLC films. The tribological properties and friction mechanism of DLC-liquid and DLC-grease composite coatings were investigated in detail under different conditions. Meanwhile, the effect of ZDDP/MoDTC ratio and their interaction on the tribological performance of the systems was also systematically investigated.

2. Experimental section

2.1. Materials and physicochemical properties

1–butyl–3–methylimidazolium tetrafluoroborate (LB104), 1–hexyl–3–methylimidazolium tetrafluoroborate (LB106), 1–octyl–3–methylimidazolium tetrafluoroborate (LB108) and 1–butyl–3–methyl imidazolium hexafluorophosphate (LP104) were prepared by previously described methods [31,32]. The physical properties of base oil (MACs and ILs) have been reported in previous work [4,7,33,34], and the information are shown in Table S1 and S2 in Supporting Information. ZDDP and MoDTC were commercially obtained. Hybrid MACs greases with ZDDP/MoDTC are defined in Table 1, and their thermal stability was analyzed by a ZRY–2P TGA with heating rate of 10 °C/min in flowing air. DLC films are based on the deposition method in Refs. [18] and [35].

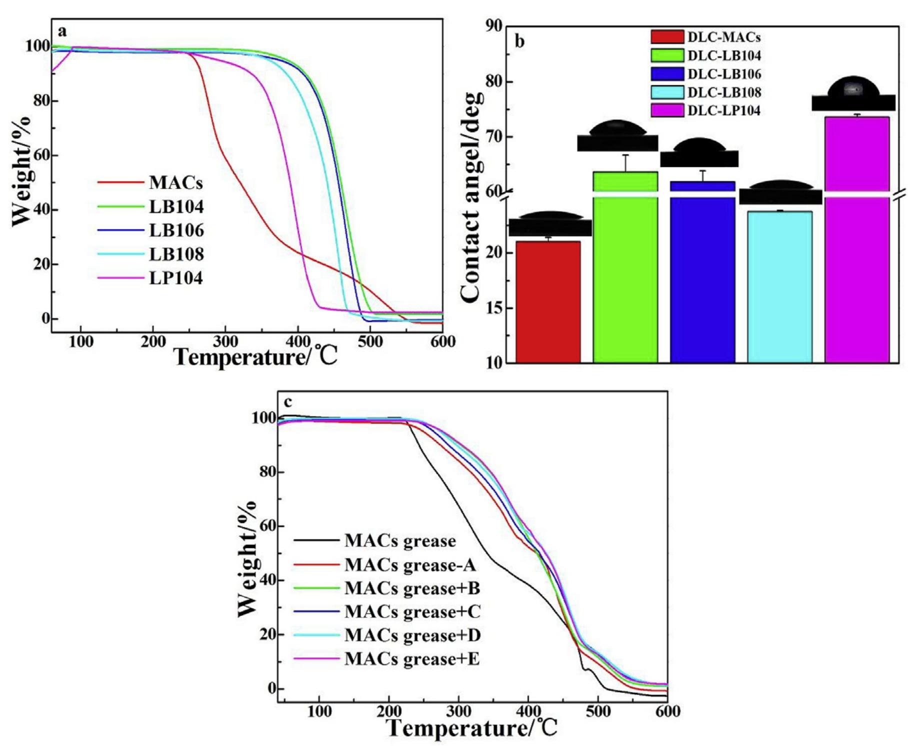

Fig. 1. TGA curves (a) of lubricants and contact angle (b) of 10 μl lubricant droplet on DLC film as well as TGA curves (c) of lubricating greases.