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Toward low friction in high vacuum by designing textured a-C/IL duplex lubricating film

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A B S T R A C T

The advanced space technologies urge us to develop a superior lubricant that owns low friction coefficient and high anti-wear abilities in high vacuum environment. Herein, we designed a novel textured a-C/ionic liquid (IL) film and investigated its vacuum tribological performance. The worn surfaces of as-deposited film and corresponding counterpart ball were investigated in detail. The results showed that the combined effect of textured grooves and IL obviously improved tribological performance of a-C film in vacuum environment. The grooves acted as IL reservoirs that promoted retention of the lubricating film and prevented direct contact between the solid surfaces. In addition, these textured grooves also acted as buffers that trapped and collected wear debris, thereby preventing the break down of the tribological system. The characterization results confirmed the formation of IL containing carbon-based tribofilm between the rubbed surfaces under joint effect of textured patterns and IL lubrication.

1. Introduction

The worldwide exploration of space environment has brought about great challenges in realizing ultralow friction, long wear life and high reliability of lubrication materials in vacuum [1–3]. Among various candidate lubricants, the amorphous carbon (a-C) film, with high hardness, chemical inertness and excellent tribological performance, has been regarded as a potential space lubricant [4–6]. Nonetheless, the limited wear life of a-C film in vacuum environment is still an insurmountable shortcoming for its wide applications in space environment, especially in heavy load and high sliding speed conditions [7,8]. The serious adhesion wear between counterpart materials and a-C film is deemed as the main reason for the rapid failure of film in vacuum environment. Up to now, many efforts have been taken to prolong the wear life of a-C films in vacuum environment. For instance, the tribological performance of a-C films can be improved by increasing hydrogen content, alloying with other elements (F, Ag, Si, Al), doping solid lubrication material (WS_2,MoS_2) and designing carbon-based films with a special nanostructure [9–13].

Alternatively, combining the unique advantages of solid lubricating coatings and space liquid lubricants, the solid/liquid synergy lubricating systems is becoming a feasible designing concept to improve the lifetime and reliability of diamond-like carbon films (DLC) in vacuum [14,15]. Ionic liquid (IL), which is salt in a liquid state, possesses many distinguished properties, such as extremely low vapor pressures, viability over large temperature ranges, excellent thermal stability, and high electrical conductivity, providing particular advantages in space based application. Recent studies on carbon film/IL synergetic lubricating coating can effectively improve tribological behavior of carbon film under high vacuum condition [16–19]. However, there still exists some shortcomings of DLC/IL duplex structure lubricating film. On the one hand, the carrying capacity of liquid lubricants is limited, as they usually undergo rheological thinning under high loads. On the other hand, the friction coefficient and wear rate of DLC/IL coatings under high vacuum conditions are still a little high. Thus, further improvement of tribological performance for this kind of new synergetic coating is required.

Recently, surface texture as a gaining momentum in tribological

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design has attracted increasing attentions because it is believed that tribological advanages, such as reduced wear, controlled friction and enhanced lubrication is accomplished through surface texture optimization [20–24]. The mechanisms of surface texture in improving the tribological performance of mechanical components are mainly ascribed to acting as reservoirs to retaining lubricants, trapping wear debris, acting as micro bearings to enhance lubrication, changing interface wetting behavior and reducing real contact area between sliding pairs. Our previous study also revealed that surface texture played a vital role in prolonging wear life of carbon film in vacuum environment [25]. Therefore, DLC/IL duplex lubricating films combined with surface textured method have remained a great interest in the pursuit of obtaining high bearing capacity and low friction in space applications. Unfortunately, no efforts have been devoted to explore the tribological performance of texture a-C film under IL lubricated condition in high vacuum environment.

Driven by the above aspects, in the present study, we first deposited a-C film on textured stainless steel substrates by magnetron sputtering technology and then chose a typical IL as space liquid lubricant. Afterwards, the tribological performance of a-C film in vacuum environment by fabricating surface textured solid-liquid synergy lubricating film was explored in detail. Meanwhile, we also comparatively studied the tribological performance of a-C film, textured a-C film and a-C/IL film. Furthermore, the friction mechanism of test samples was also discussed by taking into account the film structure and the corresponding wear tracks as well.

2. Experimental procedures

2.1. Preparation of textured a-C/IL duplex lubricating coating

The preparation process of textured a-C/IL film is illustrated in Fig. 1. The parallel grooves with uniform interval distances were produced on polished stainless steel surface (φ24 × 8 mm, 1Cr18Ni9Ti) by Nd-YSG laser equipment (Laser wavelength is 1.064 μm). The laser pulses were 4 us with impulse frequency of 2 kHz. The interval distances were set as 0.3 mm. Before the deposition of a-C film, the sharp rims on the edge of the textured grooves were polished by abrasive paper and surface roughness Ra of the polised substrate was 10–15 nm.

a-C film was deposited by medium frequency unbalanced magnetron sputtering process. Some details about this deposition system have been described in our previous reports [26]. During deposition process, graphite target (99.9%) was used as carbon source and Ar (99.9%) as sputtering gas. Firstly, the substrate was etched by plasma Ar^+ at bias voltage of −600 V to remove the adhering dust. Then, the Ti interlayer of 180 nm was coated on the etched substrate to increase the adhesion strength. Afterwards, a-C film was deposited on Ti interlayer at a pressure of 0.3 Pa. The current of graphite targets was 10 A and the pulse bias voltage of substrate was −150 V with duty cycle of 15%. The deposition time was 3.0 h and the thickness of a-C film was about 1.5 μm.

The liquid lubricants used in this study were ionic liquid (3-hexyl-1-methyl-imidazolium hexafluorophosphate, short as IL), which was purchased from Lanzhou Greenchem ILS, LICP, CAS, China. The selected IL with a extremely low vapor pressure of 2×10^{-7} Pa at the room temperature can ensure its long term operation in vacuum environment. The molecular structure and fundamental properties of IL are listed in Table 1. About 10–15 mg IL was added on the pre-deposited a-C film, then the IL layer with a thickness of 20 μm was prepared by spinning method. At last, the textured a-C/IL solid-liquid lubricating film was successfully prepared for test.

2.2. Characterizations

Microstructure of as-prepared a-C film was observed by high-resolution transmission electron microscopy. The as-deposited a-C film was first deposited on single crystallite NaCl substrate, and then collected by dissolving NaCl substrate in distilled water for TEM observation. Meanwhile, Raman spectroscopy was employed to verify the structure of as-deposited a-C film. The Raman test time was set as 60 s and the scanning range was between 800 cm^{-1} and 2000 cm^{-1}. The morphologies of as-prepared film and the corresponding wear tracks were observed by field emission scanning electron microscopy (FESEM) equipped with an energy dispersive spectrometer (EDS). The hardness was measured with a nano-indenter equipped with a Berkovich diamond probe tip. The maximum indentation depth was limited to less than 10% of the film thickness to avoid substrate effects.

2.3. Vacuum tribological properties characterization

The friction and wear tests of a-C film, textured a-C film, a-C/IL film and textured a-C/IL film were performed on a ball-on-disk tribometer inside a vacuum chamber. The detailed information

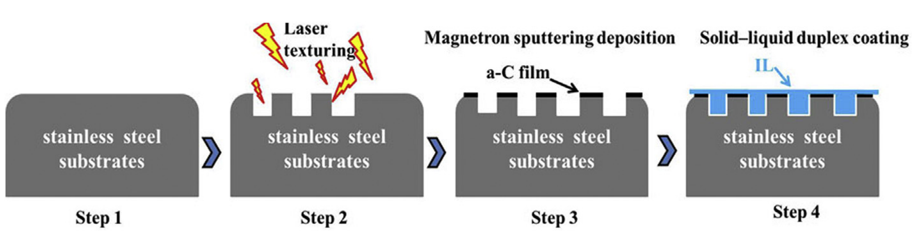
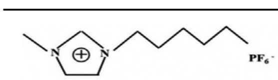


Fig. 1. The schematic illustration of the producing process of textured a-C/IL film.

Table 1
Molecular structure and properties of IL selected in this work.

Molecular structure	Deposition Temperature (T_d °C)	Kinematic Viscosity at 40 °C (mm^2/s)	Viscosity Index	Density at 15 °C (g/cm^3)
	344	129	106	1.298