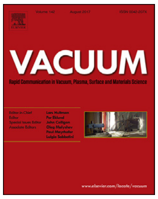
Vacuum 143 (2017) 36–39

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum



Fullerene-like nanostructure induced excellent friction behavior in high vacuum environment for hydrogenated carbon film

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ARTICLE INFO

Article history:
Received 13 April 2017
Accepted 30 May 2017
Available online 1 June 2017

Keywords:
FL-C:H film
a-C:H film
Friction
Vacuum
Mechanism

ABSTRACT

Hydrogenated carbon film (a-C:H film) with fullerene-like nanostructure has been prepared successfully by magnetron sputtering technology. Here, we investigated the film morphology, mechanical properties as well as tribological behavior in high vacuum environment. The results show that the fabricated fullerene-like hydrogenated carbon (FL-C:H) film exhibits high hardness and elasticity. Importantly, the wear life of FL-C:H film is markedly prolonged to more than 36000 cycles under a high applied load of 5 N in high vacuum environment. The outstanding tribological performance in vacuum environment can be attributed to the presence of unique fullerene-like nanostructure and friction-induced promotion of onion-like nanostructure during friction process.

1. Introduction

Nowadays, the ceaseless human exploration of space environment is critically dependent on the reliable and durability of many moving mechanical assemblies and tribological components. Developing an effective lubrication method to reduce friction and improve wear resistance for long-term operation of mechanical assemblies is a challenge for space technology and applications [1]. a-C:H film, which possesses high hardness, low friction, high chemical stability, excellent wear and corrosion resistance, is referenced as a potential space lubricating material [2–4]. However, the adhesion and cold-welding between the diamond-like carbon (DLC) film and the counterpart often occurs under high vacuum condition, resulting in a short wear life, especially for the non/low hydrogenated DLC film [5,6]. Up to now, a series of studies have been conducted to extend the wear life of a-C:H films in vacuum environment, such as 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 [7–10].

Interestingly, recent studies disclosed that the short/medium-range ordered nanostructure, such as graphene and FL, has been demonstrated as an important factor in enhancing material properties of film. Our recent work has revealed that the special graphene-like nanostructure endowed a-C:H film excellent tribological properties in vacuum environment [11]. Fullerene-like (FL) structure has been also demonstrated as an important factor in enhancing material properties of film. It has been revealed that FL nanostructure has the ability of restraining the dislocation, assisting the stress relaxation and the curved graphitic planes have a function of eliminating the energetic dangling bonds at the edge of the growing structure. For example, MoS_2, carbon nitride (CN_x), pure carbon film as well as a-C:H films with FL nano-arrangement have been aroused numerous research interest owing to their excellent tribological performance and mechanical performance [12–16]. Significantly, FL nanostructure has been proved to improve the tribological performance of a-C:H film in humid air environments and inert atmosphere dramatically [14,16]. Nonetheless, the tribological performance of FL-C:H film in vacuum environment has scarcely been reported. In the present study, we aim to incorporate FL structure into a-C:H film for achieving excellent tribological performance in high vacuum environment, and discuss the friction mechanism of FL-C:H film in high vacuum environment by taking into account microstructures, mechanical properties as well as the characterization of worn surfaces.

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http://dx.doi.org/10.1016/j.vacuum.2017.05.037
0042-207X/© 2017 Published by Elsevier Ltd.

2. Experimental details

2.1. Preparation of films

FL-C:H film and a-C:H film were deposited on polished stainless steel substrates (1Cr18Ni9Ti; φ24 mm × 8 mm, 220HV) and n-type Si (100) substrate by magnetron sputtering technology. The details about the deposition process were described elsewhere [11]. Si layer with thickness of 250 nm was deposited on the substrates firstly. Then, carbon film was deposited at a mixture gas of CH_4 (purity 99.99%) and Ar (purity 99.99%). Graphite targets (purity 99.99%) were employed as sputtering source. The preparation process of FL-C:H film and a-C:H film is controlled by regulating the periodical discharged plasma growing environment. Similar preparation methods of FL-C:H film has been reported in our previous study [16]. The deposition time of carbon film was 3.5 h, which enabled the thickness of carbon film in range of 1.5–1.6 μm.

2.2. Characterization of as-prepared film

The microstructure of as-prepared film was observed by JEOL-2010 high-resolution transmission electron microscopy (HRTEM). The Jobin-Yvon HR-800 Raman spectrometer with an Ar+ laser of 532 nm line was used to reveal the detailed bonding structures of film. The Nanotest 600 nanoindenter apparatus (Micro Materials Ltd., UK) with a Berkovich indenter at a load of 5 mN was used to evaluate the hardness of film. The elastic recovery was calculated by the formula $(d_{max}-d_{min})/d_{max}$, where d_{max} and d_{min} are the maximum and minimum displacements during unloading. The internal stress of the film was tested by the substrate curvature method [17].

Vacuum friction and wear tests were conducted with a rotational ball-on-disk tribometer that was sealed in a vacuum chamber. The details about this apparatus are described elsewhere [7]. Friction tests of GCr15 steel ball (radius: 6 mm) against as-prepared films were conducted at a normal load of 5 N (corresponding with maximum contact stress of 1.09 MPa), a pressure of 1.0×10^{-4} Pa, and a sliding speed of 300 r/min. Friction experiments were conducted at least three times under same experimental conditions to minimize errors. The structural information and phase compositions of worn surfaces were characterized by SEM, TEM and Raman spectrometry.

3. Results and discussion

Fig. 1 shows the plan-view HRTEM micrograph and Raman spectrum of FL-C:H film. In Fig. 1(a), FL-C:H film can be seen as ordered domains of several nanometers in size consisting of straight and curved planes arrangements. The curved plane with a layer spacing about 0.34 nm, is in good agreement with the layer interval of graphite (d_{002} = 3.34 Å) [14,18,19]. The buckled sp^2-hybridized plane is interlock by covalently linked sp^3 bonds to form a three-dimensional network structure, which discloses the typical features of FL-C:H film. As shown in Fig. 1 (b), Raman spectrum of FL-C:H film can be fitted at 1260, 1380, 1470 and 1570 cm^{-1} four Gaussian peak position, respectively. With reference to the previous study [18,19], the first three peaks correspond to the A-type symmetry (five-, six- and seven-membered rings, respectively), while the fourth peak near 1570 cm^{-1} is assigned to E-type symmetry (six-membered rings). Compared with the a-C:H film, the increased fraction of two peaks at 1260 cm^{-1} peak and 1470 cm^{-1} can be attributed to the increase of curved graphite sheets and fullerene structure in film [14,16]. Thus, both Raman characterization and TEM test confirms the FL structure in FL-C:H film.

Fig. 2 comparatively shows the hardness and elastic recovery of FL-C:H film and a-C:H film. Noticeably, the typical load-displacement curves significantly revealed that the elastic recovery of FL-C:H film is 85.3%, higher than a-C:H film of 77.5%. Meanwhile, FL-C:H film also exhibits higher hardness of 11.6 GPa compared with a-C:H film (9.5 GPa), suggesting that the fabricated FL nanostructure plays a vital role in determining the mechanical properties of carbon film expect to the sp^3 bonds [14,20]. Moreover, the stress test reveals that FL-C:H film possesses a lower internal stress of 0.55 GPa, while the a-C:H film is 0.88 GPa. FL nanostructure consisting of curved and interlocked sp^2 bond can prevents interplanar slip and bond breaking due to the reversible bond rotation in three dimensions structure, which endows carbon film with low internal stress, high hardness and elastic recovery.

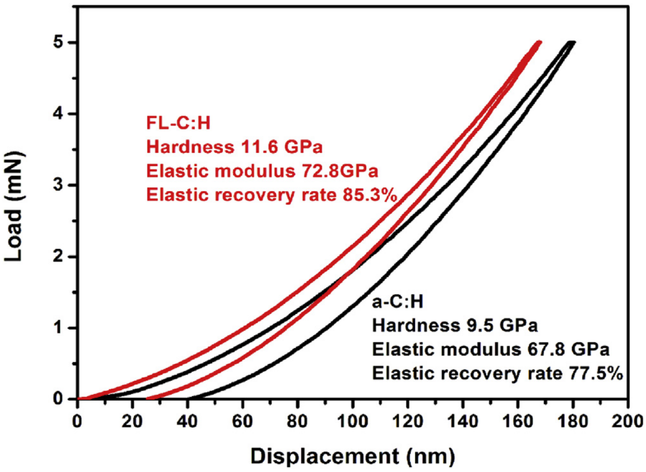

Fig. 2. Typical load–displacement curves of FL-C:H film (a) and a-C:H film (b).

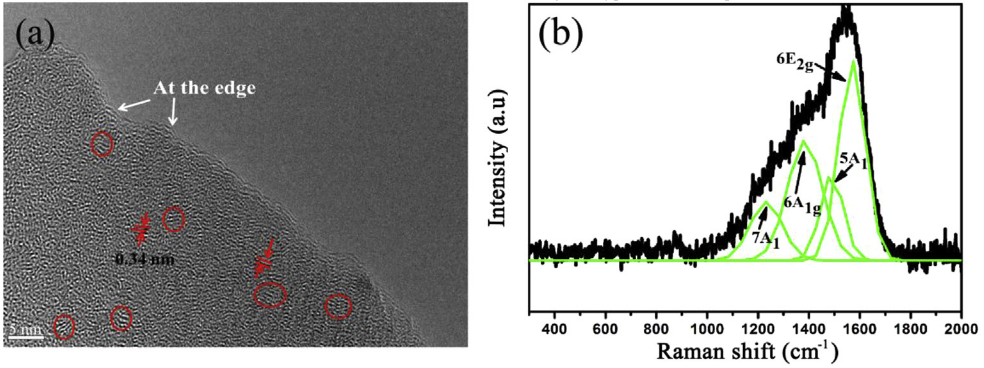

Fig. 1. HRTEM micrograph (a) and Raman spectrum of (a) FL-C:H film.