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Full Length Article

Role of humidity in reducing the friction of graphene layers on textured surfaces

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ABSTRACT

A multiple-layer graphene was prepared on steel surface to reduce friction and wear. A graphene-containing ethanol solution was dripped on the steel surface, and several layers of graphene flakes were deposited on the surface after ethanol evaporated. Tribological performance of graphene-contained surface (GCS) was induced by reciprocating ball against plate contact in different RH (0% (dry nitrogen), 30%, 60%, and 90%). Morphology and wear scar were analyzed by OM, 2D profile, SEM, Raman spectroscopy, and XPS. Results show that GCS can substantially reduce the wear and coefficient of friction (COF) in 60% relative humidity (RH). Low COF occurs due to graphene layer providing a small shear stress on the friction interface. Meanwhile, conditions of high RH and textured surface could make the low COF persist for a longer time. High moisture content can stabilize and protect the graphene C-network from damage due to water dissociative chemisorption with carbon dangling bonds, and the textured surface was attributed to release graphene layer stored in the dimple.

1. Introduction

Since the early forties, it is well known that the lubricating property of graphite is derived from its laminar structure where carbon atoms lying on the same layer are closely packed and it is strongly environment dependent. Many experimental studies investigating the influence of the gas atmosphere on the friction regime of graphite [1–4], and graphite in water can lead to ultralow friction by three-step friction test [5]. Rietsch has indicated that graphite can afford a lower friction in moisture environments due to the presence of an oriented graphite friction layer which can be formed only if the carbon dangling bonds are deactivated by water dissociative chemisorption [6]. Highly oriented pyrolytic graphite (HOPG) similar to single crystalline graphite also Show a lower friction in the humid environments, and the COF of the perpendicular surface is higher than that of the parallel surface [7].

Graphene as a fascinating 2D interfacial material had attracted considerable attention from scientists because of its unique physical, electronic, and chemical properties [8–10]. In theory, small shear force between the produced layers results in lower COF than that of graphite, thus possibly contributing to antifriction and lubrication [11]. Some authors investigate the micro-tribological behavior of graphene grown on SiC under different condition by a combination of a microtribometer with an AFM [12–15]. In the aspect of macro-scale, graphene coating deposited on the substrate is to reduce friction [16,17], and the COF of multilayered graphene is studied under different RH [18]. Berman et al. [19–22] conduct the tribological tests of graphene flakes deposited on steel surface sliding against steel balls at a normal load of 2.0 N and recorded a low COF of 0.15. Results show that this low COF can persist for 1200 cycles in N_2 atmosphere and for 47000 cycles in H_2 atmosphere because the hydrogen atoms can protect the underlying graphene surface from further damage. However, the report on the friction of graphene layer under different RH condition is fairly limited, especially on macroscale friction. The role and mechanism of water dissociative chemisorption with graphene layer during friction was not clearly.

In the present research, a graphene-containing ethanol solution was dripped on the steel surface, and the steel surface formed several-layer graphene flakes after the liquid ethanol evaporated. The motivation of this report is to investigate the durability and degradation mechanism of GCS in different RH sliding condition and analyze the role and chemisorption mechanism of water during friction, which was not reported in previous works.

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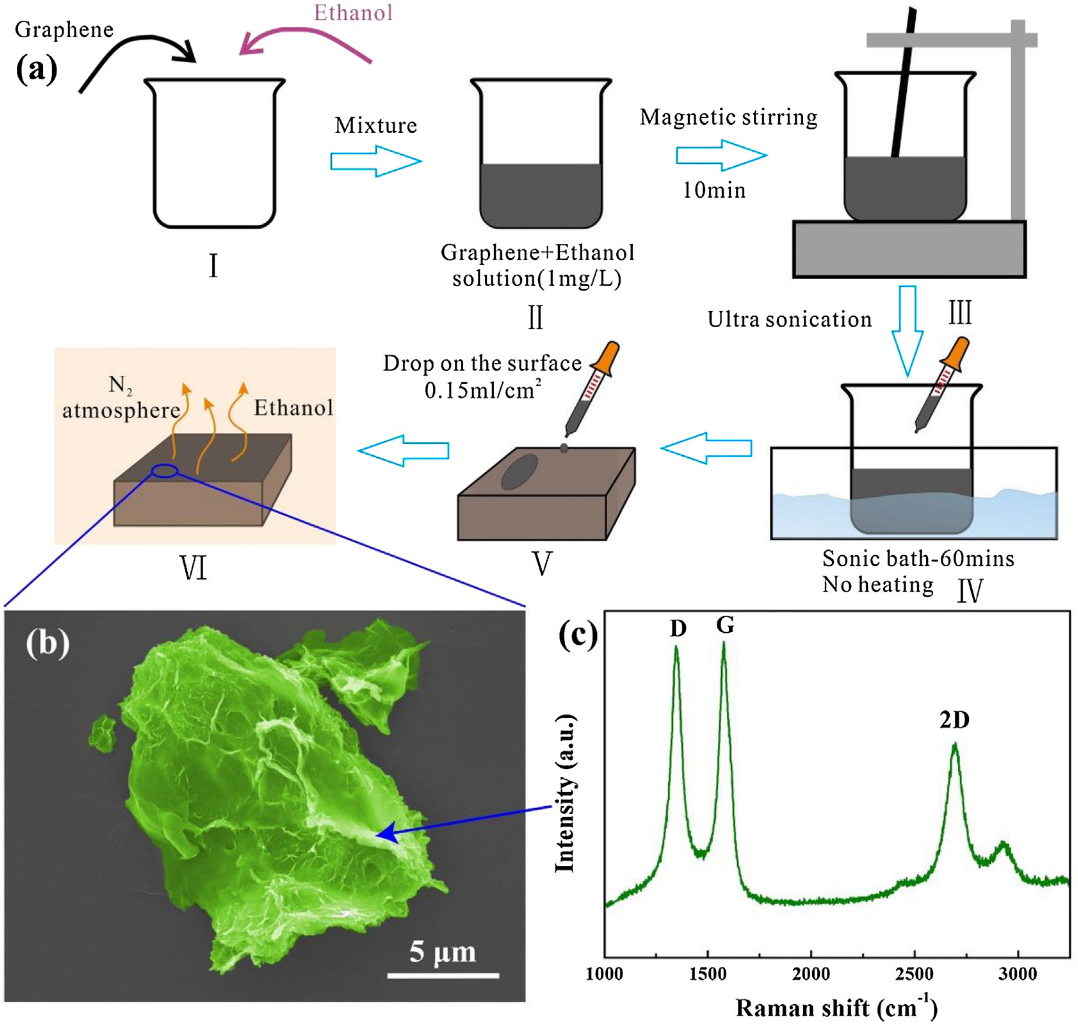

Fig. 1. Preparation process (a), SEM image (b), and Raman spectra (c) of GCS.

2. Experimental procedure

The single-layer graphene particles used in this research were purchased from Jinan Graphene New Materials. Graphene particles were added to the ethanol solution at a weight concentration of 1 mg/L. Then, graphene + ethanol solution was stirred for over 10 min and subjected to 60 min of ultrasonic vibration for uniform suspension in the ethanol solution. A 0.15 mL solution of per 1 cm^2 was applied on the steel surface in a droplet state, and the liquid ethanol part was evaporated in dry nitrogen environment to protect graphene from oxidation. Then, the steel surface would form multiple-layer graphene flakes (Fig. 1a), and the character of the graphene layer was observed by scanning electron microscopy (SEM) (JSM-7001F; JEOL, Japan). As shown in Fig. 1b, several graphene layers were irregularly distributed in the steel surface. The characteristic of graphene layer on the surface was analyzed by Raman spectrum (Lab Ram HR) characterization, utilizing a 532 nm laser as excitation source. Fig. 1c shows the Raman spectrum of the graphene layer deposited on the steel surface. Three peaks are clearly observed in Fig. 1c, particularly the D, G, and 2D peaks, which are the typical features of graphene. The D peak at 1320 cm^{-1} was known as the disorder band, which corresponds to the sp^2 hybridized health defects (graphene edge structure). The G peak at 1580 cm^{-1} indicates the vibration in all of the sp^2-bonded carbon atoms, thereby denoting a “defect-free” graphitic character. By contrast, the 2D peak at 2700 cm^{-1} reflects the thickness of graphene, especially for multiple-layer graphene. The ratio of *2D*/*G* intensity in Fig. 1c is below 1, indicating that approximately two- to four-layer graphene was deposited on the steel surface [23]. The presence of D peak is due to the partial oxidation of graphene during deposition as well as non-planar deposition of the flakes.

The steel surface with 20% area ratio round dimples was prepared by laser etching with wavelength of 1064 nm, average power of 10 W, pulse frequency of 10 kHz, and scan speed of 5 mm/s. When the laser beam hits the steel surface, a temperature gradient was generated on the surface. This temperature gradient induced the formation of a surface tension gradient toward the molten pool, causing the material to amass at the pool edge [24]. Fig. 2 shows the morphology and 2D profile of textured surface, and the dimples were 100 μm in diameter and 20 μm in depth.

Tribological performance was conducted with a ball–plate contact wear model by using a UMT-2 testing machine. The upper ball sample was GCr15 steel (wt.%: C–1.0, Cr–1.49, Mn–0.31, Si–0.26, P–0.009, and S–0.004) with a diameter of 9.525 mm and hardness of 766 HV. The lower plate specimen was 65 Mn spring steel (wt.%, C–0.68, Si–0.25, Mn–1.1, S $\le$ 0.035, P $\le$ 0.035, Cr $\le$ 0.2, Ni $\le$ 0.25, and Cu $\le$ 0.25) with hardness of 270 HV. The roughness of the ball and plate was 0.4 and 1.5 μm, respectively. During the test, the normal load was 2 N (average Hertz contact pressure was approximately 0.45 GPa); the sliding speed was 8 mm/s; the reciprocating sliding distance was 8 mm; and the test time was 1200 s in controlled RH atmosphere (0% (dry nitrogen), 30%, 60%, and 90%); The