Tribology International 92 (2015) 246–254

Contents lists available at ScienceDirect

Tribology International

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

Friction and wear behaviors of carbon and aramid fibers reinforced polyimide composites in simulated space environment

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ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form
3 June 2015
Accepted 4 June 2015
Available online 25 June 2015

Keywords:
Carbon and aramid fibers
Polyimide composites
Atomic oxygen and ultraviolet irradiations
Sliding friction

ABSTRACT

The friction and wear behaviors of carbon and aramid fibers reinforced polyimide composites have been investigated in simulated space irradiation environment and start–stop friction process. The experiment results showed that the introduction of fibers decreased the friction coefficient and improved the wear-resistance of polyimide matrix after atomic oxygen and ultraviolet irradiations especially for the carbon fibers. A start–stop friction process aggravated the wear of various composite materials against the counterpart ball. Carbon fibers reinforced polyimide displayed excellent tribological property in irradiation environment and start–stop friction condition, which was expected to become a kind of potential tribological material for the application of spacecraft.

1. Introduction

Polymer materials have been used widely in aerospace friction units during the past few decades due to their good engineering properties, e.g. low density, good mechanical properties, high wear resistance, easy manufacturing processes, excellent irradiation resistance, self-lubrication properties and chemical inertness [1–7]. The friction units materials usually should maintain stable and reliable friction coefficient in different environments. However, so far single polymer material could hardly satisfy these requests. Therefore, various fibers are incorporated into a kind of polymer matrix material to enhance the friction and wear properties, which are receiving considerable attention for applications in severe space conditions [8–11]. Various high-performance modern fibers have been used as filler for the reinforced polymers, and inorganic carbon fibers (CF) and organic aramid fibers (AF) that own excellent mechanical properties and favorable dispersion in polymers are the main candidates [12]. Carbon fiber-reinforced polymer composites have inherent advantages which highlight the high modulus, low coefficient of friction and good wear resistance [13–17]. Moreover, aramid fibers have also been proven to be an effective reinforcing agent due to high tensile strength/modulus and good thermal resistance [18–21].

As a typical thermoplastic polymer material, polyimide (PI) that owns high mechanical properties, resistance to irradiation, chemical inertness, high wear resistance, thermo-optical characteristics and easy processing has been widely used as matrix material for high performance friction materials [22–25]. Various fibers reinforced PI materials that can readily be engineered properties have widely used in aerospace, construction, and consumer products [26–29]. Though the incorporation of fibers into polymer composites have been received significant research interests, fewer studies involve the impact of harsh space environment (atomic oxygen (AO), ultraviolet (UV), proton and electron irradiation) and complex friction conditions (start–stop, high speed and high load) on the structural changes and friction performance of the fibers reinforced PI composites [30–32]. More importantly, various forms of irradiations can result in not only mass loss but also the damage of the material surface structure, which would have a severe impact on the thermal-mechanic, tribological and optical performance of the polymer [33–36]. In addition, the complex friction conditions such as start–stop could result in the severe wear of materials, which can affect the lifespan and reliability of friction units [37–39]. Therefore, the friction and wear behaviors of carbon and aramid fibers reinforced PI composites after irradiation are the very valuable work to not only understand the changes in structure and properties of polymer material in space environment, but also prepare the high-performance materials used in spacecraft.

In this paper, two kinds of PI-based composites reinforced by carbon and aramid fibers were prepared. The effect of AO/UV irradiations and start–stop friction conditions on the tribological performance of the pure PI and fiber-reinforced composites on

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http://dx.doi.org/10.1016/j.triboint.2015.06.004
0301-679X/

ball-on-disc tribometer were investigated in detail. The changes in microstructure were detected by attenuated total reflectance infrared spectroscopy (ATR-FTIR), and the morphologies of the worn surface were characterized by scanning electron microscopy (SEM) to analyze the wear phenomena.

2. Experimental

2.1. Materials

The aromatic thermoplastic polyimide powders (YS-20, shown in Fig. 1) were provided from Shanghai Research Institute of Synthetic Resins (Shanghai, China) with the inherent viscosity of 1.19 dL/g. Aramid fiber used was supplied by Shanghai Ruiyan Trading Co., Ltd. (Shanghai, China), and the average length of AF was less than 125 mm and the diameter was about 20 mm. Carbon fiber with the diameter of ca. 7 µm were purchased by Jiangsu Nantong Carbon Fiber Co., Ltd. The morphology of carbon fibers and aramid fibers were characterized by SEM as shown in Fig. 2.

2.2. Preparation of specimens

PI-based composites reinforced with carbon fibers (CF/PI) and aramid fibers (AF/PI) were prepared, respectively. The fibers were mixed with PI powder in ethanol with mechanical stirring and ultrasonic bath for 2 h to obtain the uniform mixtures, which were then filtered and dried. The weight ratios of carbon fibers and aramid fibers were 15 wt%, respectively. The mixtures were heated from room temperature to a maximum temperature of 375 °C at a rate of 2 °C min^{-1} in mold, and then held at 375 °C and 20 MPa for 90 min to form 6 mm thick sheets with intermittent bumping to release the trapped moisture. Finally, the mold in the pressure was cooled in air to room temperature. The sheets were cut into 18 mm × 18 mm × 2 mm discs for test. Before the test, the sample surface was polished to the roughness $Ra \leq 0.2$ µm and cleaned in acetone by ultrasonic.

2.3. Irradiation test

AO irradiation and UV irradiation experiments were carried out under vacuum environment using ground-based simulation facilities at Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences. AO irradiation was used a microwave power source to excite O_2 to produce oxygen plasma, which would become a beam and be accelerated towards a molybdenum plate with a negatively charged electric field. The accelerated oxygen positive ions collided with the plate and were neutralized by the negative charges and rebounded to form a neutral AO beam with impingement mean translational kinetic energy of 5 eV and flux of 6.0×10^{15} atoms · cm^{-2} s^{-1}, equal to the impact energy of AO on the surfaces of spacecraft in actual low earth orbit (LEO) space environment. The exposure period was controlled for 180 min. UV irradiation was performed in high vacuum environment (10^{-5} Pa) with a wavelength range of 200–400 nm. The typical UV energy flux was determined to be about six times the solar constant, and the exposure period was controlled as 180 min. In experiments, samples were irradiated firstly by AO, and then by UV.

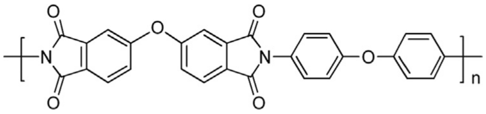

Fig. 1. Chemical structure of polyimide.

2.4. Characterization of PI composites

The infrared spectroscopic measurements were carried out on a Nexus 870 FTIR spectrometer (Nicolet, USA) using the attenuated total reflection (ATR) technique with a germanium crystal. XPS analyses were carried out on an ESCALAB 250Xi X-ray photoelectron spectroscopy instrument (ThermoFisher, America) to investigate the surface chemical composition before and after irradiations. All spectra were acquired using Al-Kα X-ray source (1391 eV) with a binding energy range of $0-1400$ eV. All binding energy were referenced to the C1s hydrocarbon peak at 284.6 eV. The worn surface morphologies and the width of the wear track were observed using a JEM-5600LV scanning electron microscope (JEOL, Japan). An optical microscope was used to observe the damage of the steel counterpart. The average roughness (Ra) was determined using a MicroXAM 3D non-contact surface mapping profiler (ADE Corporation, USA). The surface morphologies and root-mean-square roughness values (RMS) of the samples before and after irradiations have been acquired using scanning probe microscope (SPM) imaging scan in a Hysitron TriboIndenter TI-950 system (Hysitron, USA).

2.5. Friction and wear test

The friction and wear behaviors were tested with a ball-on-disc apparatus at room temperature under vacuum environment (10^{-4} Pa). Fig. 3 shows the model of friction device and formulas of wear rate. The upper specimens were GCrl5 steel ball with a diameter of 3.175 mm, which was loaded against rotating polymer discs. The disc rotated at a speed of 0.126 m/s for 1200 s with a rotational radius of 6 mm under a load of 1 N. In addition, the start–stop friction and continuous friction test were respectively carried out to evaluate the durability of the polymer materials at a speed of 0.5 m/s under a load of 5 N. In the start–stop friction test, the steel balls slid on the polymer discs for 10 min, then stop for 2 min with 5 cycles. While in the continuous friction test, the steel

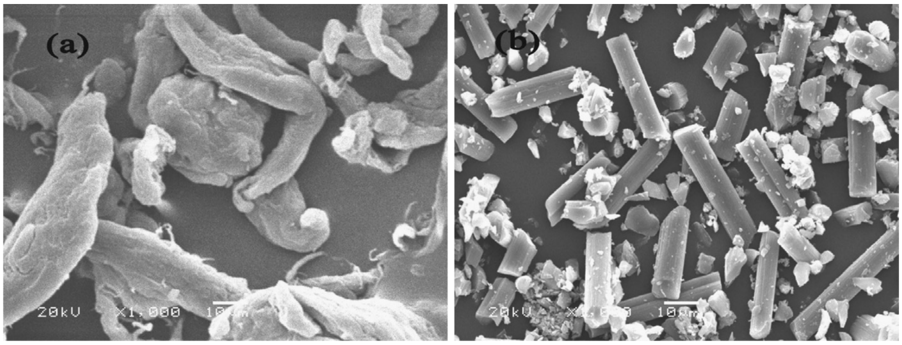

Fig. 2. SEM micrographs of aramid fibers (a) and carbon fibers (b).