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Friction and wear behavior of nanosilica-filled epoxy resin composite coatings

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ABSTRACT

Hydrophilic silica nanoparticles (abridged as nano-SiO_2) surface-capped with epoxide were dispersed in the solution of epoxy resin (abridged as EP) in tetrahydrofuran under magnetic stirring. Resultant suspension of nano-SiO_2 in EP was then coated onto the surface of glass slides and dried at 80 °C in a vacuum oven for 2 h, generating epoxy resin-nanosilica composite coatings (coded as EP/nano-SiO_2). EP coating without nano-SiO_2 was also prepared as a reference in the same manner. A water contact angle meter and a surface profiler were separately performed to measure the water contact angles and surface roughness of as-prepared EP/nano-SiO_2 composite coatings. The friction and wear behavior of as-prepared EP/nano-SiO_2 composite coatings sliding against steel in a ball-on-plate contact configuration under unlubricated condition was evaluated. Particularly, the effect of coating composition on the friction and wear behavior of the composite coatings was highlighted in relation to their microstructure and worn surface morphology examined by means of scanning electron microscopy. Results indicate that EP/nano-SiO_2 composite coatings have a higher surface roughness and water contact angle than EP coating. The EP-SiO_2 coatings doped with a proper amount of hydrophilic SiO_2 nanoparticles show lower friction coefficient than EP coating. However, the introduction of surface-capped nanosilica as the filler results in inconsistent change in the friction coefficient and wear rate of the filled EP-matrix composites; and it needs further study to achieve well balanced friction-reducing and antiwear abilities of the composite coatings for tribological applications.

1. Introduction

Polymer-matrix composites (PMCs) are subjected to abrasive wear in many applications, due to plowing by counterface hard asperities resulting in material removal and grooves. A typical field example in this respect points to the abrasive wear of facilities made of PMCs or coated with PMC coatings for coal handling and mining [1–3].

Polymer-matrix coatings, usually possessing a low shear strength and good toughness, are of particular significance in reducing friction and wear as well as extending service life of facilities involving surface contact and relative motion, due to their better cost-effectiveness than bulk materials [4–8]. Of various polymer-matrix coatings, epoxy resin (EP) coatings with good mechanical, electrical and thermal properties have been widely used in many fields including mechanical engineering, chemical engineering, and electrical/electronic engineering, as well as aviation and aerospace industry [9–14]. The practical use of EP coatings in industry, however, is seriously limited by poor impact resistance and stress cracking resistance. To overcome this drawback, researchers have made numerous attempts to modify epoxy resin by introducing various reinforcing agents and fillers including a variety of inorganic nanoparticles [15–17]. Kishore et al. [18,19] successfully improved the wear resistance of epoxy resin by filling with glass fabric and found that sliding friction and wear behavior of as-prepared glass fabric-epoxy resin composites are highly dependent on the type and amount of the filler. Suresha et al. [20] selected SiC particulate and glass fiber (GF) to simultaneously modify epoxy resin and fabricated EP–SiC–GF composites with greatly improved mechanical strength and wear resistance in dry sliding conditions, thanks to the proper combination of high specific strength and specific modulus of the ceramic particulate filler and reinforcing fiber. Ramezanzadeh et al. [21,22] found that ZnO nanoparticles were able to effectively improve the corrosion resistance and mechanical properties of epoxy resin coating. Bagci et al. [23] found that incorporating boric acid filler into neat GF/EP composite resulted in decreased erosion wear resistance. Moreover, conventional inorganic filler materials such as SiO_2, SiC, TiO_2, graphite, clay/silica hybrid and so forth have also been proven effective in improving the mechanical strength and wear resistance of epoxy resin [24–28]. Some other researchers have studied the wear of silica-filled epoxy

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resin composites, Xing and Li [29] focused on the effect of particle size on the wear behavior of nanocomposites at low levels of filler content and found the filler with smaller size seemed to be more effective in the improvement of the wear resistance of the composites. Koh et al. [30] investigated the influences of load on the abrasive wear properties of silica-filled epoxy resin composites and demonstrated that the friction coefficient and the wear rate of silica filled epoxy composites were lower than those of the pure epoxy. Jacobs et al. [31] compared the wear behavior of epoxy (EP) composites and found the optimum of the specific wear rate under both dry and aqueous conditions. We are particularly interested in modification of EP by nanosilica, in particular, nanosilica surface-capped with organic molecules containing functional group like epoxy radical, because such functionalized nanosilica may possess desired activity and functionality toward strengthening EP matrix. Therefore, SiO_2 nanoparticle was surface-modified with epoxide containing hydrophilic functional group. Resultant surface-capped nanosilica was then used as a filler to prepare EP/nano-SiO_2 composite coatings on glass slides. The friction and wear behavior of as-prepared EP/nano-SiO_2 composite coatings was evaluated and compared with that of EP coating while the surface roughness, water contact angle, microstructure and worn surface morphology of the composite coatings were taken into account.

2. Experimental

2.1. Materials

Commercial high-purity epoxy resin (E-44(6101)) was provided by Feicheng Deyuan Chemicals Company (Shandong, China) and used without any further treatment. Analytical reagent tetrahydrofuran (THF) provided by Fuyu Fine Chemical Company (Tianjin, China) was used as the solvent to prepare EP suspension. Reactive nanosilica surface-modified with epoxide (coded as RNS-E, average diameter 20–30 nm, provided by Henan Provincial Research Center for Engineering and Technology of Nanomaterials) was used as the filler to prepare EP-matrix composite coatings. Analytical reagent ethylenediamine anhydrous provided by Fuyu Fine Chemical Company (Tianjin, China) was used for curing of EP suspension. Before preparation of coatings, glass slide substrates were separately ultrasonically cleaned with distilled water and absolute ethanol for 10 min and dried with nitrogen gas.

2.2. Preparation of EP/nano-SiO_2 composite coatings

Solution of EP in THF was prepared by dissolving 1 g of EP in 10 mL of THF at ambient temperature (25 °C). Into resultant EP solution was added RNS-E at an EP to filler mass fraction of 5.9%, 11.1%, 20.0%, and 27.3% generating mixed suspensions after magnetic stirring for at least 1 h. A few drops of the suspensions were then directly coated onto glass slide substrates with a dropper and dried at 80 °C in a vacuum oven for 2 h, yielding target EP/nano-SiO_2 composite coatings denoted as EP/RNS-$E_{16:1}$, EP/RNS-$E_{8:1}$, EP/RNS-$E_{4:1}$, and EP/RNS-$E_{8:3}$ (the subscripts refer to mass fraction of EP to nano-SiO_2 filler). EP coating without nano-SiO_2 was also prepared in the same manner and used for a comparative study. In the meantime, 1H, 1H, 2H, 2H-perfluorodecyltriethoxysilane (coded as PDES; Chisso Corporation, Japan; molecular formula: n-$CF_3(CF_2)_7CH_2CH_2Si(OC_2H_5)_3$, serial no.: FAS-17, volume ratio to ethanol: 1/100) with low surface energy was spread over as-prepared EP and EP/nano-SiO_2 composite coatings using an immersion method, followed by washing with ethanol and drying in an oven at 120 °C for 1 h, yielding PDES-modified coatings (presumably they possess lowered surface energy and hence larger water contact angle).

Table 1
Surface roughness of as-prepared EP coating and EP/nano-SiO_2 composite coatings with different concentrations.

Coatings	Surface roughness R_a/μm
EP	0.652
EP/RNS-$E_{16:1}$	1.093
EP/RNS-$E_{8:1}$	1.249
EP/RNS-$E_{4:1}$	4.631
EP/RNS-$E_{8:3}$	4.558

2.3. Analysis of physico-chemical properties and microstructure of EP/nano-SiO_2 composite coatings

A Dropmaster 300 solid/liquid interface analyzer (goniometer; Kyowa Interface Science, Japan) was performed to measure the contact angles of deionized water on EP coating and EP/nano-SiO_2 composite coatings, where the static contact angles (CA) of as-prepared coatings were measured under ambient conditions. At least five repeat measurements were conducted, and newly formed sessile drop of to-be-tested deionized water with a volume of about 4 μL was used for each measurement. The averages of the repeat measurements are cited in this article.

The surface roughness and wear scar width and depth of EP coating and EP/nano-SiO_2 composite coatings were determined with a YS2206B surface profiler (Harbin Measuring & Cutting Tool Group Company Ltd., China). Wear rates of the coatings were then calculated by taking into account the load, rotary speed and time for friction and wear tests.

The microstructure of EP coating and EP/nano-SiO_2 composite coatings was examined with an Hitachi S-3200N scanning electron microscope (SEM, Hitachi Corporation, Japan; accelerating voltage 5 kV and 10 kV); where the specimens for cross-sectional SEM analysis was prepared with a pencil diamond.

2.4. Evaluation of friction and wear behavior of EP/nano-SiO_2 composite coatings

A UMT-2 multi-specimen test system (CETR, USA) was performed to evaluate the friction and wear behavior of EP coating and EP/nano-SiO_2 composite coatings sliding against steel in a ball-on-plate contact mode. The lower specimen, glass slide with EP coating or EP/nano-SiO_2 composite coatings, was driven to reciprocally slide against stationary upper ball made of 440 C stainless steel (4 mm in diameter). Before each test, the steel ball was cleaned with acetone in a supersonic bath. Reciprocal sliding tests were run at a sliding distance of 5.0 mm, temperature of about 20–25 °C, relative humidity of 40–45%, rotary speed of 30 rpm and 60 rpm, and load from 0.5 N to 4.0 N with an interval of 0.5 N, for a duration of 20 min or 4 h. Friction coefficient–time plots were automatically recorded by the test rig. The wear rates of the coatings were calculated from wear volume losses measured with a surface profiler, where the normal load and sliding distance were considered.

3. Results and discussion

3.1. Surface roughness and water contact angle of EP/nano-SiO_2 composite coatings

Table 1 lists the surface roughness of EP coating and EP/nano-SiO_2 composite coatings with different compositions. As-prepared EP coating has a surface roughness of R_a = 0.652 μm, which is much smaller than that of EP/nano-SiO_2 composite coatings. Particularly, the surface roughness of the composite coatings increases with increasing dosage of nano-SiO_2, and the composite coating made from the EP-nanosilica suspension with a filler mass