Friction and wear of epoxy composites containing surface modified SiC nanoparticles

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The authors of the present paper evaluated the sliding wear behaviors of epoxy and its composites filled with untreated and treated SiC nanoparticles. The experimental results indicate that the nanoparticles pretreated by graft polymerization of polyacrylamide effectively improved the overall performance of the matrix epoxy. In comparison with the untreated SiC nanoparticles, the grafted SiC nanoparticles led to more significant reduction in frictional coefficient and wear rate of epoxy. Even under high contact pressure, the composites with grafted SiC nanoparticles possessed the highest wear resistance. The strong interfacial bonding between the grafted SiC nanoparticles and the matrix should account for the properties enhancement. Accordingly, a feasible way of efficiently applying SiC nanoparticles to the preparation of wear resisting nanocomposites has been developed.

KEY WORDS: nanoparticles, surface treatment, polymer nanocomposites, friction and wear

1. Introduction

With the rapid development of nanophased materials in recent years, attempts have been made to make nanocomposites filled polymers for improving the latter’s tribological performance [1–10]. In comparison with micrometer particulates that are widely used in polymeric composites, nanoparticles are believed to have the following advantages [7,11]: (i) the mechanical behavior of the bulk materials can be emulated while the abrasiveness of the hard microparticles decreases remarkably owing to a reduction in their angularity; (ii) the transferred film can be strengthened as the nanoparticles would have the capability of interacting well with wear debris; (iii) the material removal of nanoparticulate composites would be much milder than that of conventional composites because the fillers have the same size as the segments of the surrounding polymer chains.

Bulk SiC has been known as the ceramic material with high hardness, wear resistance, high temperature stability and chemical inertness. Accordingly, SiC nanoparticles were employed in the preparation of wear resisting nanocomposites in hopes of imparting the excellent tribological performance of SiC to the composite materials. Xue and Wang found that under either dry or water lubrication, the wear rate and frictional coefficient of nano-SiC/PEEK composites are evidently lower than those of unfilled PEEK [2,6]. Besides, nanometer SiC is able to lower the wear of polyetheretherketone (PEEK) more greatly than micron SiC [2]. A thin, uniform and tenacious transfer film was formed on the counterpart surface in the case of carbon steel ring/nano-SiC filled composite block. It was believed that some proportion of nanometer SiC was oxidized into SiO\textsubscript{2} during the rubbing process, existing in the transfer film and the wear trace of the block [3]. As nano-SiO\textsubscript{2} in PEEK is very effective in decreasing friction and wear [1], it might partly explain why nano-SiC/PEEK system exhibits decreased the aforesaid improvement of the tribological properties.

It is worth noting that the addition of SiC nanoparticles is not bound to bring about positive effect. When polytetrafluoroethylene (PTFE) powder and nano-SiC particles were jointly incorporated into PEEK [5], for instance, the friction reduction and wear resistance capacities of the nanocomposites became worse. The reason for this was due to the chemical reaction between the nanometer SiC and PTFE during the sliding friction process. The formation of SiF\textsubscript{x} by consuming certain amount of nano-SiC and PTFE deteriorated the property of transfer film. Only when the content of PTFE was high enough, the ternary composites nano-SiC/PTFE/PEEK exhibit lower frictional coefficient than the binary ones PTFE/PEEK. Recently, Bahadur and Sunkara also reported that the wear resistance of polyphenylene sulfide (PPS) decreased with the
incorporation of nano-SiC, while the coefficient of friction with 2 vol.% SiC nanoparticles was about the same as of PPS but increased slightly with higher proportions of the filler [12].

For giving full play to nanoparticles in polymer composites, the authors considered that proper surface pre-treatment should be a pre-requisite. Comparatively, graft polymerization onto nanoparticles proved to be more efficient [13–15], as the grafted polymers would change the hydrophilic surface of the particles to hydrophobic one and break apart the nanoparticle agglomerates. In our previous work, polyacrylamide (PAAM) was covalently bonded to SiC nanoparticles [16]. The reason for using PAAM as the grafting polymer lies in that the amide groups on PAAM chains would take part in the curing reaction of epoxy besides the above advantages [14,15]. A strong filler/matrix interfacial adhesion can thus be established in case PAAM grafted nano-SiC is compounded with epoxy, which might improve the overall performance of the composites. In this paper, sliding wear behaviors of epoxy based composites with untreated SiC nanoparticles and grafted SiC nanoparticles are studied to evaluate the feasibility of the surface treatment technique. Also, it is expected that a nanocomposite with enhanced tribological performance can be acquired.

2. Experimental

2.1. SiC nanoparticles and their surface treatment

The nanosized SiC provided by Hua-Tai Co. Ltd., China, were in its α-phase, with a specific surface area of 15.2 m²/g and an averaged diameter of 61 nm, respectively. Prior to use, the particles were dried in an oven at 110 °C under vacuum for 24 h in order to get rid of the physically absorbed and weakly chemically absorbed species. The morphology of the particles can be found elsewhere [16].

Surface modification of the nanoparticles was conducted by introducing reactive functional groups (i.e., double bonds) onto the nanoparticles using silane coupling agent followed by radical grafting polymerization of acrylamide. The details of the reaction procedures have been described in Ref. [16]. The percentage of grafting is 10%. To remove the homopolymerized PAAM absorbed on the particles, the grafted nanoparticles were extracted with water for over 72 h. For the convenience of discussion, the grafted nanoparticles before and after the extraction are denoted by SiC-PAAM and SiC-g-PAAM, respectively.

2.2. Epoxy based composites manufacturing

Bisphenol-A epoxy resin (type E-51) was provided by Guangzhou Dongfeng Chemical Co., China. The curing agent 4,4-diaminodiphenylsulfone (DDS) was supplied by Shanghai Medical Agents Co., China. The composite materials were fabricated by mixing the (untreated or treated) SiC nanoparticles and epoxy together with a fast stirring for 2 h and then ultrasonic agitation for 1 h. The stirring process was carried out in vacuum to improve the dispersion and to avoid generation of air bubbles during compounding. After that, the mixture was heated to 130 °C and the curing agent was added under continuous stirring. Then the composite system was poured into a pre-heated mould and the curing procedure began after the extraction of possible air bubbles for 1.5 h. The curing proceeded step by step as follows: 3 h at 100 °C, 2 h at 140 °C, 2 h at 180 °C, and 2 h at 200 °C.

2.3. Characterization

Unlubricated sliding wear tests were carried out on a block-on-ring apparatus and a pin-on-disk apparatus under a constant velocity of 1 m/s, respectively. The former was used for determining specific wear rate, while the latter for frictional coefficient. Both the steel ring and disk have an initial surface roughness of 0.1 μm. Prior to wear testing, all the samples were pre-worn to average their surface conditions and to reduce the running-in period. The actual steady-state test period was set to 10 h for wear rate tests and 20 h for frictional coefficient determination, respectively. After and before the wear test, a weight measurement of specimens was conducted separately to calculate the weight loss during the test. For each measurement, four specimens were tested under the same conditions.

The dispersion of the nanoparticles in epoxy composites was monitored by a Philips EM400 transmission electron microscope (TEM). The worn surfaces of the composites were observed by a JEOL-5400 scanning electron microscope (SEM) and a UBM laser profilometer, respectively. X-ray energy distribution spectra (EDS) of the counterpart steel rings were collected with a LINK-ISIS 300 apparatus at an accelerating voltage of 20 kV.

3. Results and discussion

Figure 1 shows the frictional coefficient of the SiC nanocomposites as a function of SiC content. Although the untreated SiC nanoparticles are capable of lowering the frictional coefficient of epoxy, the grafted nanoparticles can provide more remarkable effect of solid lubrication. At a SiC loading of 0.2 vol.%, for example, the coefficient of friction of SiC-g-PAAM/epoxy composites is only about 67% of the unfilled version. With a rise in filler concentration, however, the frictional coefficients of both untreated and treated SiC composites increase. It might be due to the fact that the increased