The Performances of BMI Nanocomposites Filled with Nanometer SiC

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ABSTRACT: Nanocomposites of bismaleimide (BMI) with different proportions of nanometer SiC were prepared by a high shear dispersion process and casting method at elevated temperature. The mechanical and tribological properties of the nanocomposites were investigated. The bending strength and impact strength of the nanocomposite specimens were determined, and the sliding wear performance of the nanocomposites was investigated on an M-200 friction and wear tester. The dispersion of nanometre SiC was observed with a transmission electron microscope (TEM), while those of the worn surfaces and transfer films on the counterpart steel ring were observed with a scanning electron microscope (SEM). The experimental results indicate that the nanocomposites exhibited lower friction coefficient and wear loss as well as higher bending and impact strength than BMI resin under the same testing conditions. The lowest wear rate was obtained with the nanocomposite containing 6.0 wt % SiC, while the highest mechanical properties were obtained with the nanocomposite containing 2.0 wt % SiC. The wear mechanism of the nanocomposite is mainly adhesion wear, while that of pure BMI resin is mainly fatigue cracking with plastic deformation. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 95: 1246–1250, 2005

Key words: bismaleimide; tribological properties; hardness; mechanical properties; TEM

INTRODUCTION

In recent years, inorganic nanoparticle/polymer nanocomposites have been of interest because they showed much better mechanical, tribological, and multifunctional behavior than the polymer matrices and their composites counterparts with conventional micrometer inorganic particulate.[1–3] One of the distinct advantages of nanocomposites over micronanocomposites is that the performance improvement is often acquired at relatively low concentrations of the nanofillers.[4,5] This is beneficial to the mechanical properties, processability, and aesthetic appearance of the end-products. Certainly, the performance of nanocomposites is influenced extensively by the filler morphology, size, volume fraction, and dispersion.

Bismaleimide (BMI) resin shows outstanding thermal, mechanical, and electrical properties as well as resistance to solvent and radiation. BMI matrix nanocomposites are widely used in some of the most important and complex high performance applications, ranging from military programs such as the Air Force to electronic engineering.[6] There are many reports on modification of BMI to improve its toughness.[7,8] However, there are a few reports on the tribological performances of BMI and those that exist focus on the erosion wear properties of the material. In 1989, Mathias[9] investigated the erosion behavior of a graphite-fiber–reinforced BMI polymer composite with angular aluminum oxide erodents impacting the surface. The results suggest that the erosion rate of the composite is dominated by the brittle graphite fibers, resulting in erosion rates much higher than those of the matrix polymer. Subsequently, Brandstadter and coworkers[10] obtained the same results–the erosion rate of the graphite-fiber–reinforced BMI compositions was higher than that of BMI specimens. These results imply that BMI resin has good tribological properties by nature. In our previous work, we found that BMI composites with nanometer Si_3N_4 have good sliding wear performance under nonlubricating conditions.[11]

Nanometer SiC has been shown to reduce the friction coefficient and to increase wear resistance of polyetheretherketone [12–14] or epoxy.[15] This is due to the high hardness, high chemical stability, and high thermal conductivity of SiC. In this paper, we investigated the mechanical and tribological properties of BMI-based nanocomposites filled with different proportions of nanometer SiC particles.

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EXPERIMENTAL

Raw materials and specifications

Nanometer SiC particles with diameters smaller than 100 nm were purchased from Shenyang Institue of Metal Research, Chinese Academy of Science and dried before use. 4,4′-Bismaleimidodiphenylmethane (BMI) was purchased from Hubei Fenggang Chemicals, China. BMI is a commercial-grade yellow power containing more than 85% of maleimide double-bond structure. *o,o′*-Diallylbisphenol A (DABPA) was purchased from Sichuan Jiangyou Material, China. It is an industrial-grade, amber-colored viscous liquid at room temperature.

Preparation of the nanocomposites of BMI filled with nanometer SiC

The nanocomposites of bismaleimide filled with nanometer SiC were made by the casting method. First, nanometer SiC was ultrasonically dispersed in acetone for about 10 min. Both BMI and BA were heated at 120°C for 15 min under vigorous stirring to form a clear homogeneous prepolymer. The fillers with desired proportions were then carefully mixed with the prepolymer by a mechanical high shear dispersion process. The mixture, consisting of prepolymer, the nanometer filler, and acetone, was heated to 120°C in an oil bath and kept at this temperature for 30 min with stirring to evaporate acetone. The mixture then was poured into a preheated mold with release agent and evacuated for an additional 30 min at 120°C to remove air bubbles. The pure material was prepared by a similar method as described above without addition of nanometer SiC and acetone. Finally, all of the samples were cured following these procedures step by step: 2 h at 150°C, 2 h at 180°C, and 4 h at 220°C. A postcuring process took place at 250°C for 6 h.

Measurement of the properties of materials

The bending strength and impact strength were carried out according to GB/T2570–1995 and GB/T2571–1995 (Chinese Standard), respectively. Hardness was measured according to HG2–168-65 under a loading of 62.5 kg and a steel ball with a diameter of 5 mm.

The sliding wear properties were conducted on a M-200 model friction and wear tester according to GB3960–83 (Chinese Standard). The contact schematic diagram of the frictional couple is shown in Figure 1. The accuracy of the machine can achieve 5% in measuring the frictional force. Sliding was performed under ambient conditions over a period of 2 h at a sliding speed of 0.42 m/s and under a load of 196 N. Before each test, the counterpart carbon steel ring and BMI matrix or its composite block was abraded with No. 900 water-abrasive paper, and then the steel ring and the nanocomposites blocks were cleaned with cotton dipped in alcohol and dried. The density of the filled BMI samples was measured by Archimedes principle using absolute alcohol as the immersion medium. The mass loss can accurately be measured by determining the weight of the specimen before and after the experiment. The accuracy of the weight of samples can reach 0.1 mg. A characteristic value, which describes the wear performance under the chosen conditions for a tribosystem, is the specific wear rate ω, which was calculated from the relationship

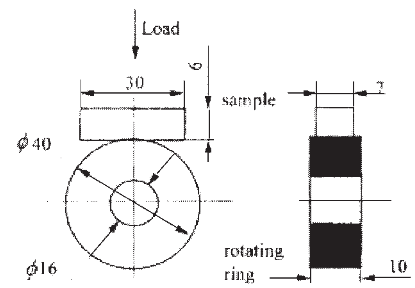

Figure 1 The contact schematic diagram for the frictional couple.

$$\omega = \frac{\Delta m}{\rho \times F_N \times L}$$

where Δm is the worn specimen mass (g), ρ is the composite specific gravity (g/cm^3), F_N is the normal force (N), and L is the sliding distance (m).

The morphologies of the worn surfaces and wear debris were observed using a HITACHI S-570 model scanning electron microscope (SEM). The distribution of nanometer SiC particles in BMI matrix was verified with a transmission electron microscope (TEM).

RESULTS AND DISCUSSION

The mechanical properties of the BMI-based nanocomposites

Figure 2 shows the mechanical properties of BMI nanocomposites with different proportions of nanometer SiC. It is seen that the bending strength and impact strength of the nanocomposites are increased at a mass fraction of the nanometer SiC content below 2.0 wt %. The bending strength and impact strength of the nanocomposites are decreased with increasing nanometer SiC content above 2.0 wt %, but are still higher than that of the BMI matrix; the best mechanical properties were obtained with 2.0 wt % nanometer SiC. This implies that the interfacial interaction between the BMI matrix and the nanometer SiC reinforcing agent is strong. Figure 3 shows TEM photographs of the nanocomposites with different contents of nanometer SiC. It can directly be seen that the SiC particles

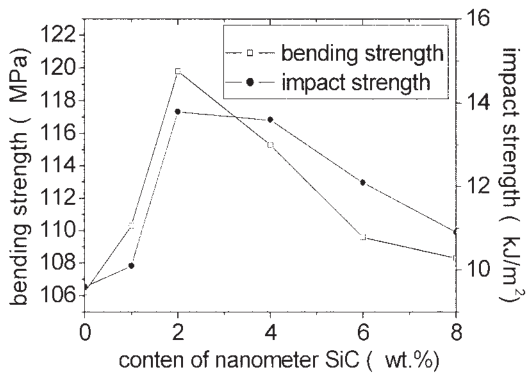

Figure 2 The mechanical properties of the nanocomposites with different proportions of nanometer SiC.

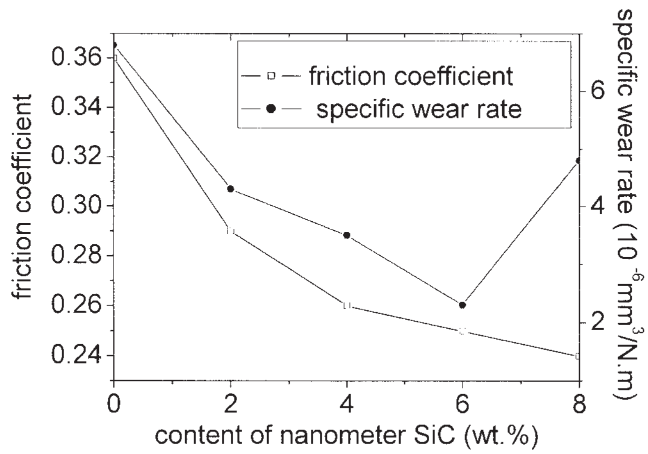

Figure 4 The frictional coefficient and wear rate of BMI nanocomposites with different proportions of nanometer SiC.

are dispersed homogeneously in resin matrix with a diameter of about 80 nm when the content of nanometer SiC is 6.0 wt % [Fig. 3(a)]. However, when the nanometer SiC content is 8.0 wt % [Fig. 3(b)], the nanometer SiC particles are dispersed with more difficulty due to the their strong agglomeration tendency and the incompatibility between inorganic SiC particles and organic resin matrix.

The sliding wear properties of the BMI-based nanocomposites

Figure 4 shows the frictional coefficient and specific wear rate of BMI nanocomposites filled with different proportions of nanometer SiC powder. It is seen that the frictional coefficient decreases with the increase of the mass fraction of nanometer SiC. For example, the frictional coefficient is reduced from 0.36 to 0.25 when SiC content increased from 0 to 6.0 wt %.

The BMI nanocomposites filled with nanometer SiC exhibit a considerably decreased wear rate in comparison with the unfilled BMI matrix. The minimum wear rate is observed at 6.0 wt % nanocomposites. The wear rate of the composite then rises with the further increase of the filler mass fraction but it is still lower than that of the neat resin. The best combination of frictional coefficient and wear rate is for 6.0 wt % nanometer SiC composites.

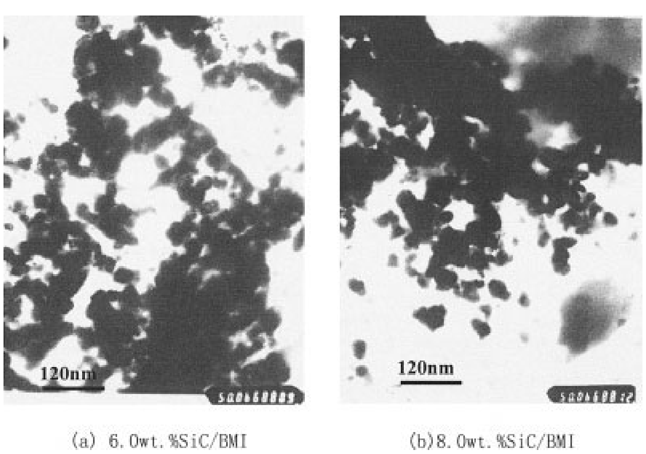

Figure 3 TEM photograph of the nanocomposites with different contents of nanometer SiC: (a) 6.0 wt % SiC/BMI; (b) 8.0 wt % SiC/BMI.

The wearing mechanisms of the BMI-based nanocomposite

To understand the effect of the nanometer SiC on the friction and wear behavior of the BMI nanocomposites, the morphologies of the nanocomposites' worn surfaces and the counterpart steel rings were studied by SEM.

Figure 5 shows the SEM pictures of the worn surfaces of pure BMI and the nanocomposite blocks with different proportions of nanometer SiC. It is noted that the obvious triangular shape opens in the wear direction and some cracks across the wear tracks on the pure BMI block indicate the severe lowing of the polymer surface by the counterpart ring surface and results in fatigue cracks during the friction process [Fig. 5(a)]. In other words, for the unfilled BMI matrix, the fatigue crack is the main wear mechanism due to acting pressure and shear loads induced by the movement of the steel counterpart.

In contrast, the surface of the worn nanocomposites filled with nanometer SiC appears to be completely different. The worn surfaces of the nanocomposites containing 2.0 and 6.0 wt % SiC are very smooth [Figs. 5(b) and (c)]. For nanocomposites containing 6.0 wt % SiC, the worn surfaces looks quite smooth beside the thin resin sheets to be removed [Fig. 5(c)], which corresponds to the lowest specific wear rate as shown in Figure 4. The fact particularly indicates that a uniform

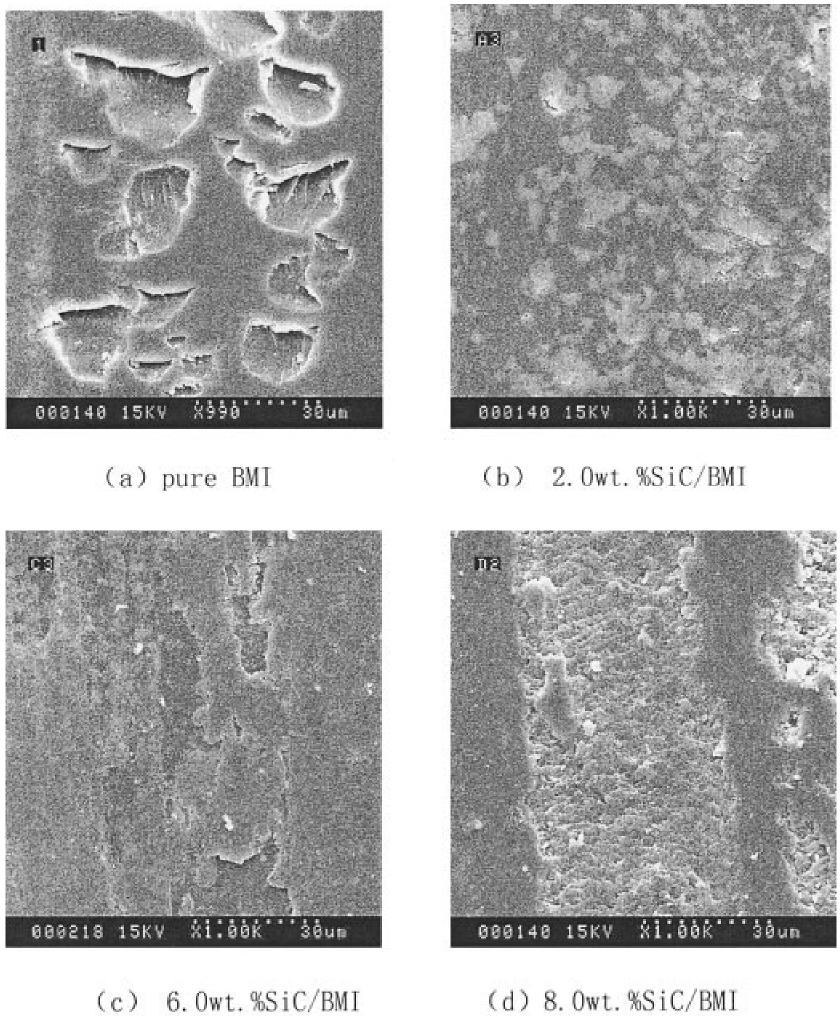

Figure 5 SEM photographs of the worn surface of pure BMI and its nanocomposites with different contents of nanometer SiC: (a) pure BMI matrix; (b) 2. 0 wt % SiC/BMI; (c) 6.0 wt % SiC/BMI; (d) 8.0 wt % SiC/BMI.

and tenacious transfer film was formed on the counterpart ring surface. Moreover, flake-like wear debris of the resin matrix and tiny particulate wear debris of the nanocomposites are observed in their sliding against the steel, respectively. The tiny particulate wear debris is prone to form a thin, uniform, and tenacious transfer film on the counterpart steel surface.[16] This principle was also embodied in Figures 6(a) and (b). It was only the transfer film that was responsible for the reduced the friction coefficient and specific wear rate of nanocomposites. During the following process they may reveal abilities to protect the material from severe wear. Naturally, the changes from severe wear of pure BMI to mild wear of the nanocomposites results from the nanometer SiC particles dispersing homogeneously in resin matrix. The interaction between the nanoparticles and BMI matrix was strong as discussed above.

For the nanocomposites containing 8.0 wt % SiC, the scuffing of the scale-like wear patterns [Fig. 5 (d)] are visible, resulting from the nanoparticles pulled out of the matrix and then further moved across the surface by scratching and rolling. Due to their agglomeration, the nanoparticles should be able to move into gaps and asperities on the counterpart surface and may then be exposed to a rolling rather than a sliding movement.[17] The resulting wear mechanism of the nanocomposites containing 8.0 wt % SiC should be described as an abrasive wear accompanied by fatigue cracking of the matrix.

Surface hardness is generally taken as one of the most important factors that govern the wear resistance of materials. That is, the stiffer the composites, the lower the frictional coefficient, so that the stick-and-slip phenomenon can be prevented.[18] The hardness of the nanocomposites was measured in this paper. Figure 7 shows that the hardness of the nanocomposites was increased with increasing the content of nanometer SiC. This indicates that nanometer SiC is beneficial for increasing the load-carrying capacity of the BMI nanocomposites. Furthermore, the dimensional stability of the nanocomposites is superior to that of pure

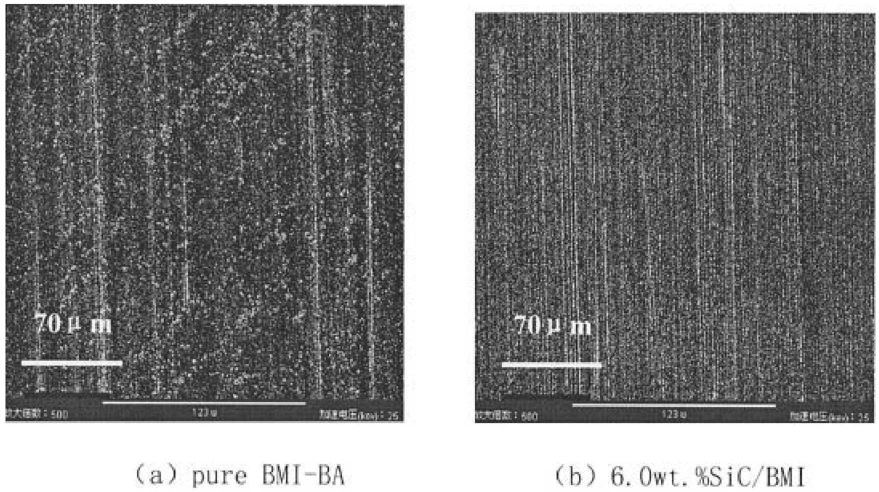

Figure 6 SEM micrographs of the transfer film on the counterpart steel surface: (a) pure BMI-BA; (b)6.0 wt % SiC/BMI.

BMI due to nanometer SiC having high thermal conductivity during the repeated friction of the specimens, which favors the reduction of the frictional coefficient.[15] Therefore, mechanical properties are not the only influential factors to improve the tribological performance, hardness enhancement should also account for the improved friction and wear properties of the nanocomposites.

CONCLUSIONS

From the above, the following conclusions can be drawn:

1. The suitable dispersion of nanometer SiC particles in BMI matrix can increase the bending and impact strength of the nanocomposites. The best mechanical properties are obtained with the nanocomposite containing 2.0 wt % SiC.
2. Nanometer SiC as a filler in BMI can significantly reduce the friction coefficient and wear rate during the dry friction condition. The lowest wear rate is obtained with the nanocomposite containing 6.0 wt % SiC.
3. The severe fatigue wear of unfilled BMI resin can be changed into mild abrasive wear with the addition of nanometer SiC particles.
4. The mechanical properties and the hardness enhancement as well as the suitable dispersion of nanometer SiC particles in BMI matrix are effective ways to improve the friction and wear properties of the nanocomposites.

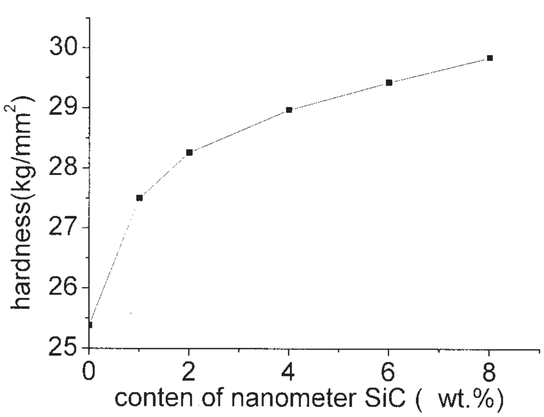

Figure 7 The hardness of the BMI nanocomposites with different proportions of nanometer SiC.

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