The Effect of Carbon Fiber Content on the Friction and Wear Properties of Carbon Fiber Reinforced Polyimide Composites

Jian Li, Xianhua Cheng

School of Mechanical & Power Engineering, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China

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ABSTRACT: The current study examines the tribological performance of polyimide and carbon fiber reinforced polyimide (CF/PI) under dry sliding condition. Different contents of carbon fibers were employed as reinforcement. All filled and unfilled polyimide composites were tested against CGr15 ball and representative testing was performed. The effects of carbon fiber content on tribological properties of the composites were investigated. The worn surface morphologies of neat PI and its composites were examined by scanning electron microscopy and the wear mechanisms were discussed. Moreover, all filled polyimides have superior tribological characteristics to unfilled polyimides. The optimum wear reduction was obtained when the content of carbon fiber is 20 vol %. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 107: 1737–1743, 2008

Key words: tribological; polyimide; SEM; wear reduction

INTRODUCTION

Polyimide and its composites attract extensive concern by tribological scientists world-wide because of their high mechanical strength, high wear resistance, good thermal stability, high stability under vacuum, good antiradiation, and good solvent resistance.[1,2] To further improve the mechanical and tribological performance of polyimide-based friction material, one of the most efficient methods is to add various kinds of fibers into the matrix as reinforcement. The addition of fibrous reinforcement plays a major role in maintaining strength, stiffness, thermal stability, and frictional properties of the composite material.[3]

Fillers, in the form of particulates and fibers, are often added to polymeric materials to improve their stiffness and strength. This second phase filler material will influence the wear resistance of the composite material. There are many references that illustrate the influence of fillers and fiber reinforcement on the abrasive wear resistance of polymeric composites.[4,5] Fiber reinforcements, e.g., carbon, glass, and aramid fibers, are the main candidates and have been widely employed. Many investigations have shown that the incorporation of fiber reinforcement can improve the wear resistance.[6–11] Attempts to understand the modifications in the tribological behavior of the polymers with the addition of fillers or fibers reinforcements have been made by many researchers.[9,12] Except for a few exceptions,[13] the wear resistance was improved with lower fiber content generally, e.g., GF or CF filled PEN, PEEK, PA, and so on.[14,15] This was attributed to a reduced ability of lowing, tearing, and other nonadhesive components of wear by the fibers, provided good interfacial adhesion between the matrix and the fiber reinforcement existed.[13] Carbon fiber reinforcement dominates in high-performance applications because of its outstanding mechanical properties combined with low weight.

Under controlled testing a given phase shows a specific wear mode and wear rate, which is determined by its individual properties. Consequently, when various phases are combined to form a multiphase material, it is expected that the overall performance will be a function of the respective contribution of each phase.[16] Nevertheless, the influence of the structure of composites on abrasive wear is a complex function of the properties and interactions of the matrix, the reinforcing constituent, and the interface between them and experimentally, it is found that fillers can either enhance or degrade the wear resistance of polymeric composites.[17]

The research on the friction and wear of thermoplastic polyimide and its composite is scarce. The purposes of the present article are to clarify the tribological behavior of neat PI and carbon fiber reinforced PI composites sliding against CGr15 ball

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Correspondence to: J. Li (lijian2008d@sina.com).
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TABLE I
The Properties of Carbon Fibers and Thermoplastic Polyimide

	Carbon fiber	GCPI^{TM}-J33AGLW
Density (kg/m^3)	1740	1530
Linear density (mg/m)	56	
Tensile strength (MPa)	2000	100
Linear resistance (Ω/m)	650	
Diameter (μm)	7	
Breaking elongation (%)		8
Flexural strength (MPa)		160
Impact strength (kJ/m^2)		15

under dry sliding condition, so as to provide some practical guidance for the use of this kind of composites under dry sliding condition. The effects of filler content on the tribological properties were also comparatively discussed and the wear mechanisms of the composites were discussed based on the SEM examination of the worn surfaces.

EXPERIMENTAL

Materials and specimens

For the present investigation, GCPI^{TM}-J33AGLW thermoplastic polyimide powder was used as the matrix. The reinforcements were polyacrylonitrile (PAN) based high strength (HS) carbon fibers. The properties of these fibers and thermoplastic polyimide are given in Table I.

Preparation process

The composite specimens were prepared by screw in-line type injection molding machine. And the component of composite includes 10, 20, and 30 vol % carbon fibers, respectively. The injection molding technique is according to Table II.

Friction and wear tests

Friction and wear tests were done using a ball-on-block reciprocating UMT-2MT tribometer at room temperature with a relative humidity of 30–45%. The specimens were polished using a fine grade SiC emery paper and cleaned ultrasonically with acetone and dried before testing. The reciprocating friction stroke was 5 mm and tests were conducted at a normal spring-driven load. Five tests were conducted under each test condition and the average values of measured friction coefficient, and wear volume were used for further analysis.

RESULTS AND DISCUSSION

Measured friction coefficient

Presented in Figure 1 are the typical evolutions of the friction coefficient of neat PI and CF/PI composite as a function of time at the reciprocating sliding frequency 4 Hz under 9 N applied load. In this study, the mean value of friction coefficients of the last 1600s sliding time was taken for evaluating the friction coefficient of the PI and carbon fiber filled PI composite. It can be seen that the friction coefficient of neat PI increases quickly during the whole process. While that of 20 and 30 vol % CF/PI significantly follows a parabolic pattern: the friction coefficients increase with respect to time and arrive at a relatively stable value at last. For 10 vol % CF/PI, the friction coefficient increases during early testing and then decreases to a steady state, thereafter suddenly increases. After that, it stays at a constant level for the remaining period of the test.

The variations of friction coefficient of neat PI and CF/PI composite are shown in Figures 2 and 3. It is seen in Figure 2 that friction coefficients of all filled PI composites and neat PI increase as the load increases from 6 to 15 N under the same reciprocating sliding frequency 4 Hz. And the friction coefficient decreases as the reciprocating sliding frequency increases from 1 to 12 Hz under the same load 9 N (Fig. 3). The composite exhibits better friction behavior since the reinforcing carbon fibers can reduce effectively the adhesion force and the plough. Moreover, 20 vol % carbon fiber reinforced PI composite exhibits the lowest friction coefficient. The addition of the carbon fibers strengthened the combination of the interface between the fibers and the PI matrix and increased the elastic modulus of the PI composites. This would be the reason why the friction coefficient of the CF/PI was reduced. As a hard phase in the soft polymer matrix, carbon fibers can reduce the true contact area with the counterbody under certain load.[18] As a result, it exhibits an important influence on reducing the plough and the adhesion between the relative sliding parts. The carbon fibers influence

TABLE II
The Injection Moulding Technique

Charging barrel (°C)						
Discharge jet	Leading portion	Intermediate section	Posterior segment	Mould temperature (°C)	Injection pressure (MPa)	Molding cyclic (s)
365	360	355	340	120–150	150–200	20–50

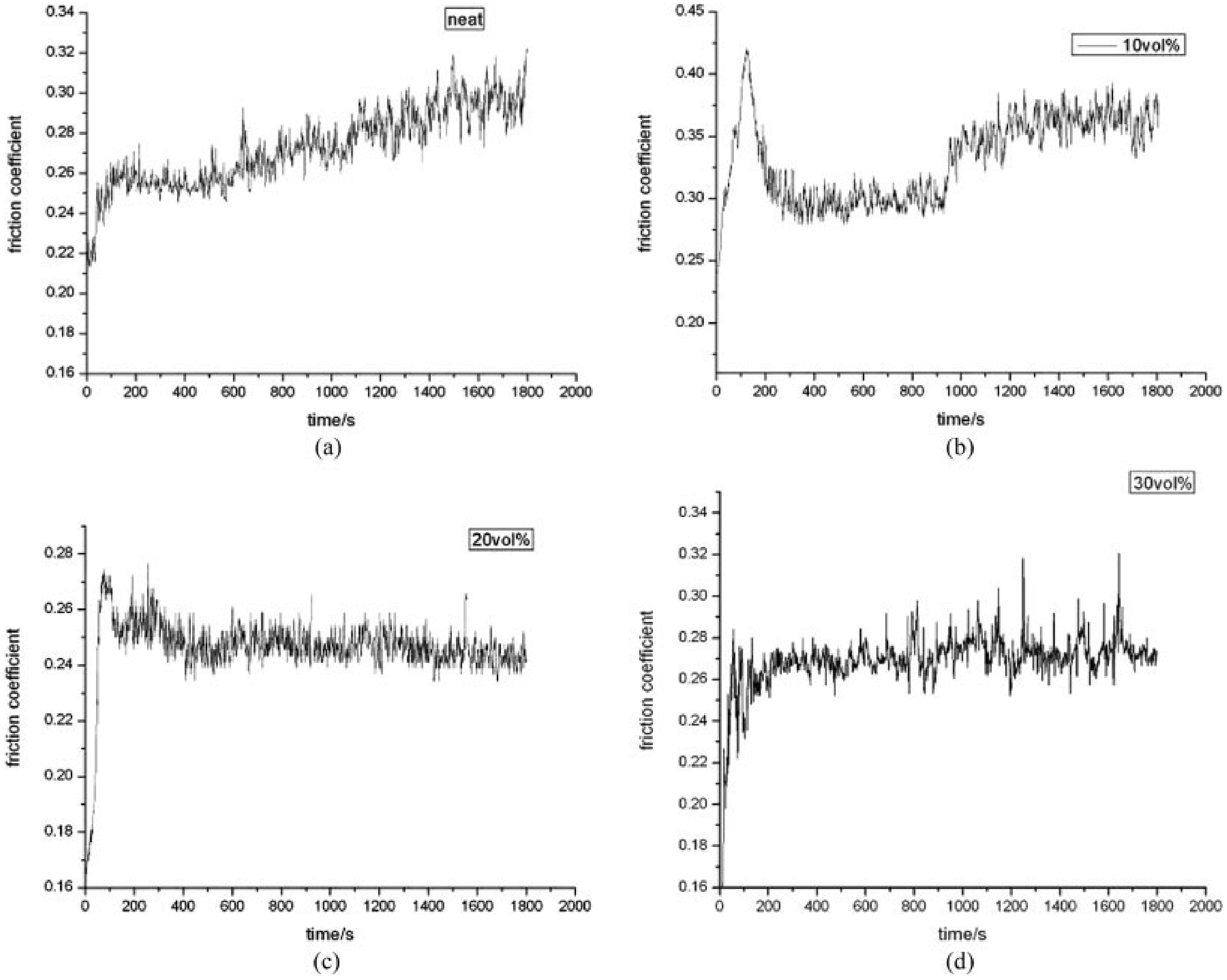

Figure 1 Friction coefficient versus sliding time at 9 N normal load and 4 Hz reciprocating sliding frequency for (a) neat PI, (b) 10 vol % CF/PI composite, (c) 20 vol % CF/PI composite, (d) 30 vol % CF/PI composite.

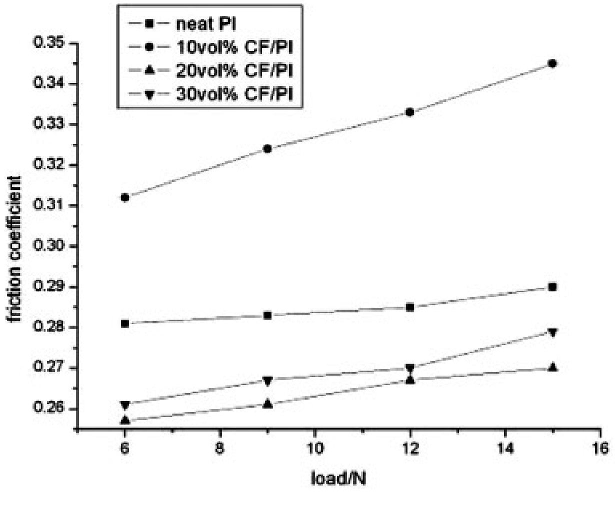

Figure 2 Variations of friction coefficient with load (reciprocating sliding frequency: 4 Hz).

the tribological behavior of CF/PI in two aspects: firstly, it could lead to fractures in the interface of the two constituents; moreover, it could reduce the plough and the adhesion between the two sliding bodies. These two roles simultaneously influence the friction and wear behavior according to the sliding conditions. Interfacial fractures will appear on worn surface of CF/PI. Filled with lower content carbon fibers, the composite exhibits higher friction coefficient compared with pure PI, so the higher friction coefficients in these cases appear to be derived from the activation of fracture in the interface of reinforcing fibers and PI matrix as interfacial energy dissipation mechanism during the sliding process.[19] While for PI composite filled with higher carbon fiber content, the lower coefficients of the friction compared with pure PI may result from the role CF played. For CF is a graphitized carbon with the hexagonal planes of its crystals aligned perpendicular to the fiber axis. The lubricating function of graphitized

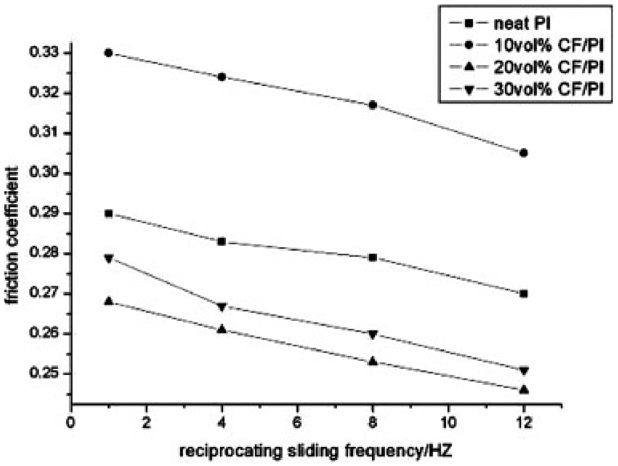

Figure 3 Variations of friction coefficient with reciprocating sliding frequency (Load: 9 N).

carbon is thought to be responsible for the reduction of friction coefficient as its composites slide against steel.[20–22] It is well documented fact that the CF can decompose into graphite crystals, which have very good lubricating properties.[23] The graphite debris forms a thin lubricating film on the counterface, thereby reducing the abrasion process drastically. This resulted in low friction coefficient and low wear of the composite compared with neat PI. With increase in reciprocating sliding frequency, the extent of fiber damage and compaction of graphite crystals increased resulting in more reduction in friction coefficient. A few fibers are microcracked, some are pulverized and some are broken into long pieces. The multiple layers of granular wear debris of the carbon fibers accumulated near the edge. Such compacted particles of carbon fibers are responsible for very low friction coefficient because of their inherent lubricating action. While the increase of load will increase the temperature of composite more remarkably, thus the adhesion effect will increase the friction coefficient.

Wear of the neat PI and the CF/PI composites

Figure 4 shows the volumetric wear of unfilled PI, and of the CF/PI composite as a function of the load applied. In general, the volumetric wear for unfilled and all filled PI composites increased with increasing applied load, but they exhibit different relationships between volumetric wear and load. The volumetric wear of the neat PI and PI composites filled with 10 or 20 vol % of filler carbon fibers showed little increase with load while that of the PI composites filled with more filler fibers (30 vol %) showed a sudden increase between loads of 9 and 15 N. Moreover, it can be seen from Figure 4 that the addition of carbon fibers can improve the wear resistance of the PI composites and 20 vol % carbon fiber reinforced PI composite exhibits the lowest volumetric wear. The unfilled PI composite showed, in general, the highest volumetric wear of all the specimens tested under the same sliding condition. Additionally, the high percentage (30 vol %) of fillers in composite degraded the wear resistance of the CF/PI because the fillers themselves caused stress concentrations in the matrix. Furthermore, the detachment of fillers causes the adjacent matrix to be poorly supported and, hence, is subjected to greater stress and thus more susceptible to fracture.

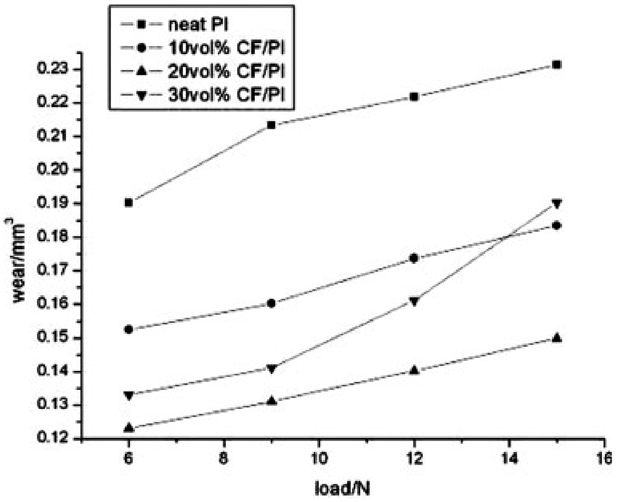

Figure 4 Variations of friction coefficient with load (reciprocating sliding frequency: 4 Hz).

Figure 5 also shows clearly that in most test conditions, 20 vol % carbon fiber reinforced PI composite exhibits the lowest volumetric wear, while neat PI shows the highest. The increase of reciprocating slid-

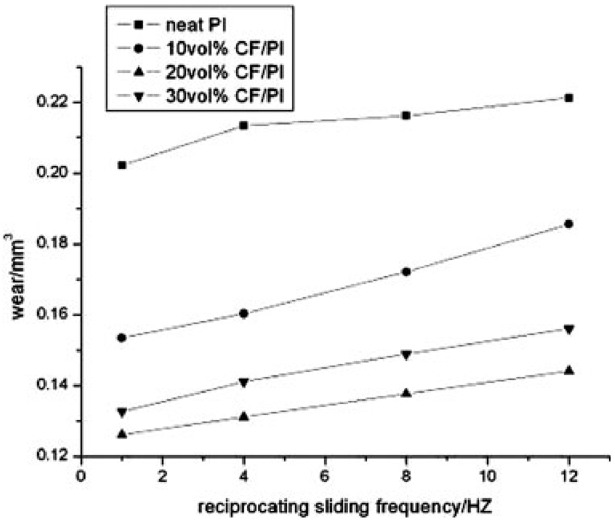

Figure 5 Variations of friction coefficient with reciprocating sliding frequency (load: 9 N).

ing frequency provokes evident varieties of volumetric wear.

The dependence of the volumetric wear on reciprocating sliding frequency can be attributed to the friction-induced heat effects. Most energy dissipated during sliding is transformed into heat and a high temperature gradient develops in the normal direction to the surface.[24] As a result of the low thermal conductivity of PI, frictional heat being generated during sliding surely provoked an increase of the contact temperature and the increase of reciprocating sliding frequency can be quantitatively correlated to the increase of sliding temperature.[25] Thus, the deterioration of mechanical properties such as hardness and shearing strength occurs as a result of interfacial temperature rising caused by friction-induced heat. Accordingly, the applied load can lead to more severe deformation of the composite under higher reciprocating sliding frequency.

Some frictional work was required to drag or to dig the carbon fibers off the matrix since the carbon fibers were limited by the PI matrix. These help to reduce material adhesion to the disc surface and bulk temperature of the wear surface. So, the addition of some certain carbon fibers can improve the wear resistance of the PI composites. As the wear reducing mechanism of reinforced fibers, Hanmin et al.[26] and Friedrich[27] proposed that the fibers support a great portion of the applied load to reduce the direct interaction between polymer and counterface. But, when the carbon fiber content was over a certain one, the wear resistance was, in turn, reduced because the fibers would be easily cracked or even dragged due to the lower continuity of the PI matrix and poor harmonization of deformation of the fibers with the matrix under the alterative interaction of the asperities of the counterface during sliding. Moreover, stress concentration is easily occurred at the interface because of inhomogeneous plastic deformation between reinforcement and matrix and provides preferential sites for stress concentration.[28,29] The composite that contained a higher fiber fraction may produce more abrasion debris, which contributes negatively to the wear resistance. The higher the CF content, the more the stress concentration sites will be.

SEM studies on worn surfaces

The worn surfaces of the neat PI and CF/PI composite under the same load and reciprocating sliding frequency are shown in Figure 6. In the case of unfilled PI [Fig. 6(a)], microcracks and peeling of PI were observed. And microcracking of the matrix material was the main wear mechanism operative. The matrix material exhibited very poor wear resistance in wear tests as it was removed. The microcracks would be originated and extended through the contacting surface layer of the PI composites in sliding since there existed the tensile stress on the surface layer behind the contacting asperities and the compressive stress on the surface layer before the contacting asperities, which resulted in a strain fatigue wear. A topography like this is conducive to abrasion of the soft polymer material and so the volumetric wear would be high.

Large sections of removal as seen here was not observed in the case of CF/PI composite, as seen in Figure 6(b–d). As the likelihood of abrasion in this case decreased markedly, wear was also reduced compared with that of the unfilled PI. In other words, changes in the topographical features accounted for the wear reduction mechanism.

Some debris were attached in the form of flakes. This feature suggests that fatigue wear is the main wear mechanism of CF/PI composite. The worn surface of the 10 vol % CF/PI sample is shown in Figure 6(b). Microcracks were observed at the surface either at the fiber-matrix boundary or at weak spots in the matrix and eventually led to delaminatation of the matrix material. Low content of carbon fiber cannot support the load from the counterface sufficiently. That means that the matrix far away from the carbon fiber has the same wear mechanism with neat PI.

Figure 6(d) shows a large crack in the matrix, normal to the sliding direction, which formed after neighboring fillers had been detached. This would give rise to a high volume loss of matrix. Microcracking and subsequent spalling of material is an important wear mode for high content filled polymeric materials. The fiber tips were clearly observed, protruding out of the polymer surface. Evidently, this is so because CF has much better mechanical properties and wear resistance compared with matrix material. Probably, a crack follows the fiber-matrix interface and passes between the fibers at their closest distance. The crack propagates under the original surface matrix layer and causes fragments of the matrix to be broken off, leaving the fibers bare. The driving force for the crack comes from the friction forces being applied on the matrix surface. Where the fibers are close to each other, the matrix between the fibers are often fragmented and broken off when the crack propagates along the fiber surface. In addition, the fibers separated from the surface layer at the sliding contact interface of the PI composites were resulted in the occurrence of the three body abrasion. Plastic deformation occurred under sliding load together with some irregular shape debris. Figure 6(d) also shows that large filler fibers were fractured into fragments and many small filler particles were detached from the matrix material leaving cavities in the matrix. These cavities

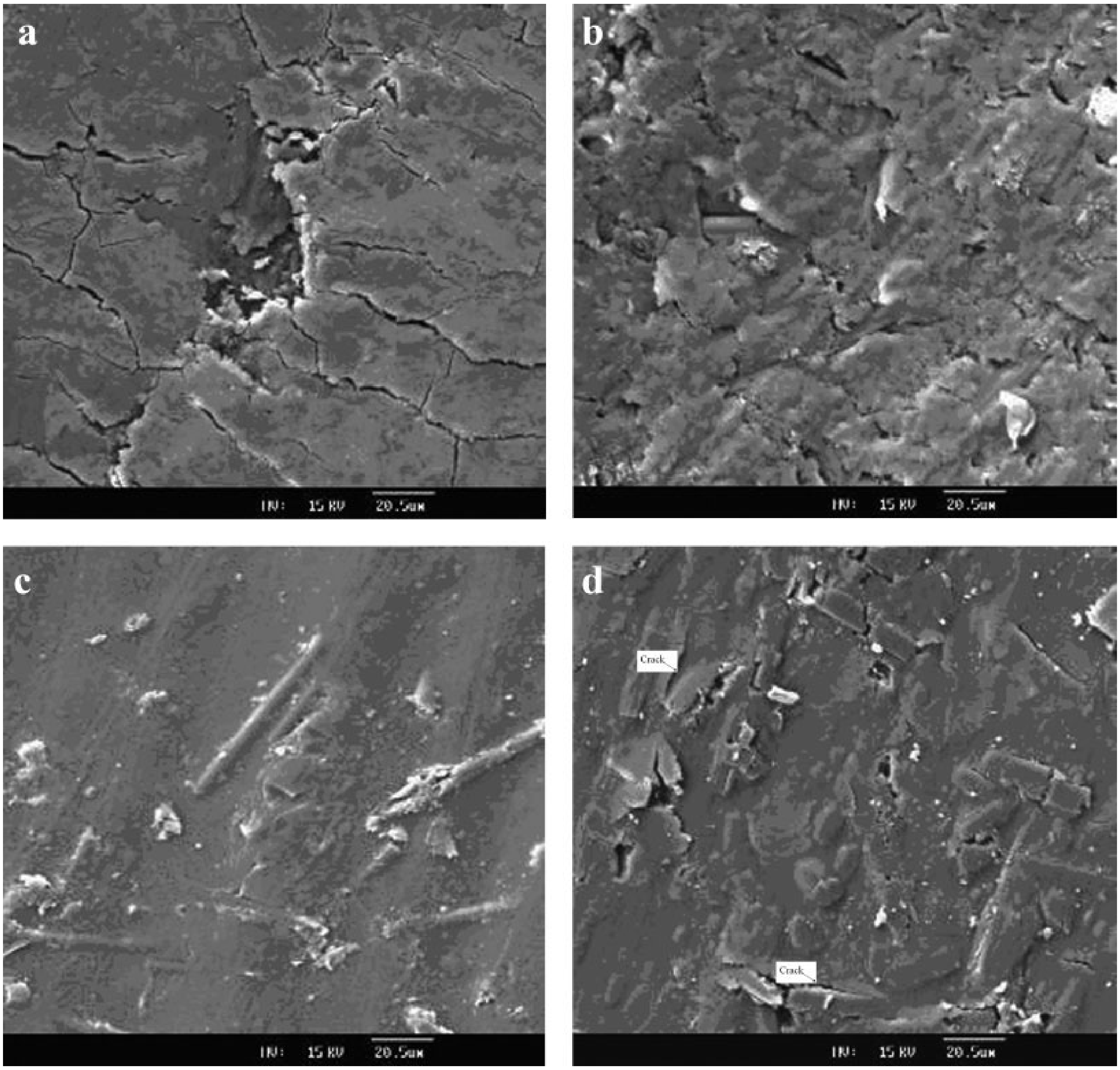

Figure 6 SEM morphologies of the worn surface of neat PI and CF/PI composites at a load of 9 N and a reciprocating sliding frequency of 4 Hz. (a) neat PI, (b) 10 vol % CF/PI composite, (c) 20 vol % CF/PI composite, (d) 30 vol % CF/PI composite.

were themselves stress concentrations and resulted in more cracks in the matrix and a higher volumetric wear. Large sections of matrix were removed causing even larger filler particles to be detached from the matrix. Thus the fillers do not now support the load resulting in a sudden increase in the volumetric wear. In conclusion, wear of polyimide composites is influenced by the properties of the filler, of the matrix and of the interface, by the relative hardness of the filler to that of the abrasive grit or counterface, by the content, distribution of filler, by the abrasiveness of filler against the matrix. Additionally, the cavity shown in the matrix is the result of a filler particle detaching from the matrix due to loss of matrix around it and poor adhesion between the filler and matrix.

While for the 20 vol % CF/PI composite [Fig. 6(c)], the worn surface is relatively smooth and the peeling of matrix and carbon fibers are constrained because of that the carbon fibers effectively support the load from the conuterface.

CONCLUSIONS

1. The incorporation of carbon fiber into PI can either increase or reduce friction coefficient and

reduce volumetric wear of the materials in sliding against stainless steel under dry sliding condition. The optimum wear resistance property was obtained at the carbon fiber content of 20 vol %.

2. The friction coefficient of neat PI and CF/PI composites increases with the increase of the load and decreases with the increase of the sliding frequency. While the volumetric wear of neat PI and CF/PI composites increases with the increase of load and reciprocating sliding frequency.
3. The adherence and plastic deformation are primary wear mechanisms for the neat PI under dry sliding. When incorporated with carbon fiber, the adherence and plastic deformation are greatly reduced.

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