Tribological Behavior of Kevlar Fabric Composites Filled with Nanoparticles

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ABSTRACT: The friction and wear characteristics of ZnO- or montmorillonite-nanoparticle-filled Kevlar fabric composites with different filler proportions when sliding against stainless steel pins under dry friction conditions were studied, with unfilled Kevlar fabric composites used as references. The worn surface and transfer film of Kevlar fabric composites were then examined with a scanning electron microscope. It was found that ZnO and montmorillonite as fillers could improve the tribological behavior of the Kevlar fabric composites with various applied loads, and the best antiwear property was obtained with the composites containing 5 wt % ZnO or montmorillonite. This indicated that these nanoparticles could prevent the destruction of Kevlar fabric composites during the friction process. The transfer film established by these nanoparticles during the sliding wear of the composites against their metallic counterpart made contributions to reducing the friction coefficient and wear rate of the Kevlar fabric composites measured in the test. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 111: 2419–2425, 2009

Key words: composites; fibers; fillers; resins

INTRODUCTION

High-performance organic fibers have become very important in recent years. Kevlar fibers are the best known among high-performance, synthetic, organic fibers.[1] Kevlar fibers were introduced in the early 1970s. As the fiber industry matured and costs began to decrease, the demand for Kevlar fibers grew steadily for munitions and commerce. In the early 21st century, the demand for Kevlar fibers has far exceeded the demand for polyacrylonitrile-based carbon fibers.[2,3]

Because of the rigid chain structure, Kevlar fibers exhibit higher tensile strength and thermal resistance. They are used in thermally resistant clothing and protective vests and helmets, as reinforcements for mechanical rubber goods and polymer matrix composites, in mechanical rope, and in sporting goods.[4–9] Moreover, Kevlar fibers alone or blended with other fibers are used to fabricate composites with resins in a variety of patterns, such as preimpregnated fabrics.[10–15] Fabric composites are attractive because they are lighter, stronger, and stiffer than conventional polymers and metals. Their additional advantage is that their properties and forms can be tailored to meet the needs of specific applications, such as advanced bearing liner materials and bulletproof composite materials.[16]

In the bearing industry, abrasion poses a great threat to the durability of bushing materials; accordingly, the study of the tribological performance of Kevlar fabric composites (KFCs) is extremely necessary. The purpose of this study was to investigate and compare the effects of two nanoparticles, ZnO and montmorillonite (MMT), on the tribological behavior of KFCs and to extend the application of Kevlar fabric or blended fabric composites in dry-sliding bearings. The mechanism of nanoparticle action in improving the tribological behavior of KFCs is also discussed.

EXPERIMENTAL

Materials

The Kevlar fabric (plain weave with an area density of 260 g/m^2) used in this study was woven from Kevlar fibers (Kevlar 49) purchased from DuPont, Inc. (Shanghai, China). Kevlar fibers are generally considered to be composed of poly(*para*-phenylene terephthalamide) (PPTA; Scheme 1). Table I presets the physical properties of the Kevlar fibers used in this work. The adhesive resin (phenolic resin) was provided by Shanghai Xingguang Chemical Plant

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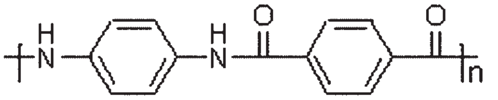


Scheme 1 Structural formula of PPTA.

(Shanghai, China). ZnO (25 ± 5 nm) was provided by Zhejiang Hongsheng Material Technology Limited Co. (Zhejiang, China). MMT (<25 nm) was provided by Zhejiang Fenghong Clay Chemicals Limited Co. (Zhejiang, China).

Specimen preparation

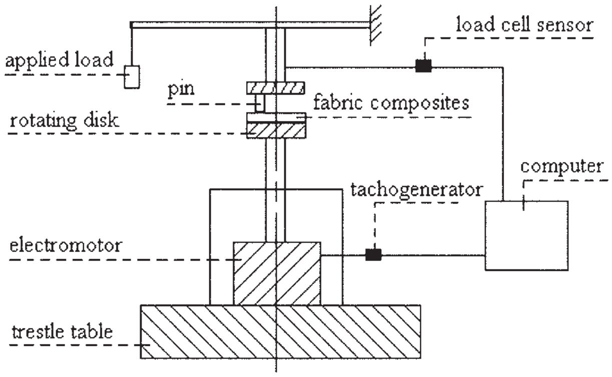
The Kevlar fabric was cleaned by Soxhlet continuous extraction in petroleum ether and then in acetone and dried at 80°C for 24 h. The nanoparticles were uniformly mixed with a phenolic resin at the proper mass fraction with the assistance of magnetic stirring and ultrasonic stirring. The content of nanoparticles in the prepared specimen was varied from 2 to 10 wt %. Then, the Kevlar fabric was impregnated in the mixed adhesive containing nanoparticles and dried. The relative mass fraction of the Kevlar fabric was about 65 ± 5%. Finally, the impregnated Kevlar fabric was affixed to AISI-1045 steel (surface roughness = 0.45 μm) with the phenolic resin and then cured at 180°C for 2 h under a certain pressure. For comparison, the unfilled KFCs were prepared in the same way. The ZnO-filled, MMT-filled, and unfilled KFC specimens were prepared and tested.

Friction and wear test

The friction and wear behavior of KFCs was investigated with a Xuanwu III pin-on-disc friction and wear tester (Scheme 2). The pin-on-disc test consisted of loading a stationary pin sliding against a rotating disc, which was affixed with Kevlar fabric/phenolic composites. The flat-ended AISI-1045 pin was fixed on a loading cantilever beam with a chuck. The applied load was loaded onto the pin according to the principle of moment balance. The distance between the center of the pin (diameter = 2 mm) and axis was 12.5 mm, resulting in an apparent contact area of about 1.57 × 10^{-4} m^2. The pin stayed over the disc with two degrees of freedom: a vertical one, which allowed normal load application by direct contact with the disc, and a horizontal one for friction measurement. The electromotor had tachogenerator feedback to ensure stable running speeds.

TABLE I
Physical Properties of Kevlar 49

Material	Kevlar 49
Fiber fineness (denier)	800
Density (g/m^3)	1.44
Tensile strength (GPa)	3.4
Tensile modulus (GPa)	130
Breaking elongation (%)	2.4
Decomposition temperature (°C)	500



Scheme 2 Schematic diagram of the pin-on-disc wear tester.

Before the tests, the pin was polished with 350-, 700-, and 900-grade water-proof abrasive papers to a surface roughness of 0.15 μm and then cleaned with acetone. The sliding was performed under ambient conditions (temperature = 25°C, relative humidity = 40%) with a rotation speed of 0.26 m/s and a load between 156.8 and 219.52 N over a period of 2 h under dry conditions. At the end of each test, the wear volume loss of the composites was calculated by the measurement of the depth of the wear scar with a micrometer with a 0.001-mm resolution. The wear performance was expressed in terms of the wear rate:

$$w = V/P \times L \qquad (1)$$

where w is the wear rate [$m^3(N\ m)^{-1}$)], V is the wear volume loss (m^3), P is the load (N), and L is the sliding distance (m). The friction coefficient was obtained directly from the computer running the friction-measure software. The software measured the friction coefficient from the friction force gained by a load cell sensor. Each experiment was carried out three times, and the average value was used. The morphologies of the worn surface of the KFCs and the counterpart pin were analyzed on a JSM-5600LV scanning electron microscope.

RESULTS AND DISCUSSION

Tribological properties of the KFCs

In Figure 1, the friction coefficient and wear rate of the unfilled KFCs and KFCs filled with different ZnO mass contents are plotted versus the load. With the rise in the ZnO content, both the friction coefficient and wear rate of KFCs increase initially and then decrease. This indicates that the filler content

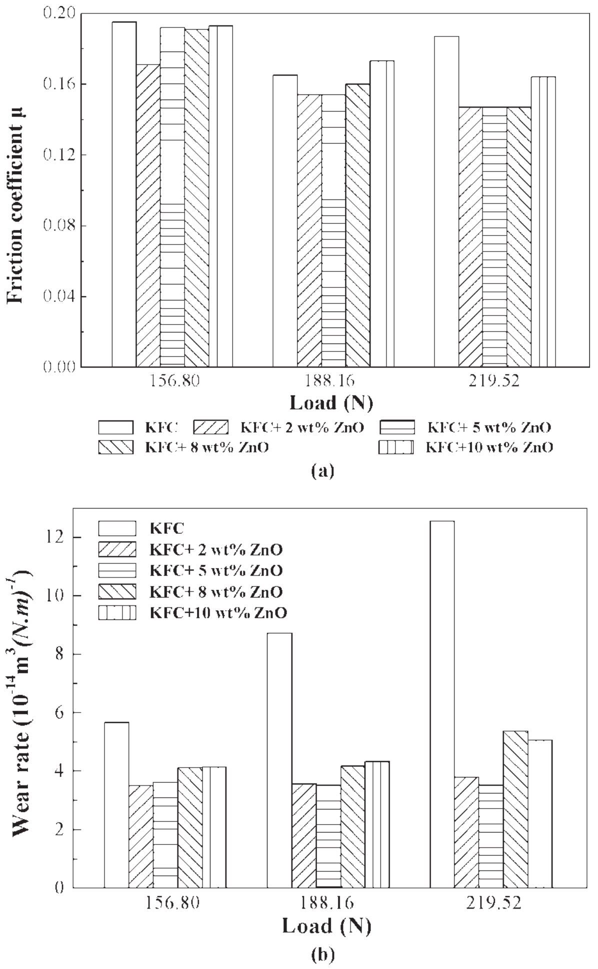


Figure 1 Variation of (a) the friction coefficient and (b) wear rate with the load for KFCs filled with different ZnO contents (0.26 m/s).

plays a role in the tribological behavior of the KFCs. The friction coefficient is best when the composites contain 2 wt % ZnO, and the wear rate is best when the composites contain 5 wt % ZnO. The friction coefficient of the KFCs with different ZnO contents decreases as the load increases, whereas the wear rate increases slowly with the increase in the load. The wear rate of the KFCs filled with 5 wt % ZnO seems independent of the load. The basis for the wear rate calculation formula (although the wear rate is unchanged), the wear volume loss, also increases with the increase in the load. Comprehensively considered, KFCs filled with 5 wt % ZnO contribute the best antifriction and antiwear properties.

Figure 2 shows the dependence of the friction coefficient and wear rate of the unfilled KFCs and KFCs filled with different MMT mass contents on the load. The friction coefficient of the KFCs decreases with the content of MMT rising, but the friction coefficient of the KFCs filled with 10 wt % MMT is in contrast at 219.52 N. Under different load conditions, the wear rate of the KFCs decreases initially and then increases with the rise in the MMT content. The friction coefficient of the KFCs filled with 2 or 5 wt % MMT decreases with the increase in the load, whereas the friction coefficient of the KFCs filled with 8 or 10 wt % MMT decreases first and then increases; this is similar to what was found for the unfilled composites. The wear rate of the unfilled KFCs and those filled with different MMT contents increases with an increase in the load. When the load is 219.52 N, the unfilled KFCs and those filled with 10 wt % MMT reach the ultimate loading capacity; therefore, the wear rate is relatively great. The wear rate shows a monotonic increase with increasing load. This is because the friction surface temperature goes up with increasing load, and this results in the adhesion of the composite to the counterpart surface and thus reduced wear resistance.

The friction coefficient and wear rate of the unfilled KFCs and those filled with 5 wt % ZnO or 5 wt % MMT are plotted in Figure 3 as a function

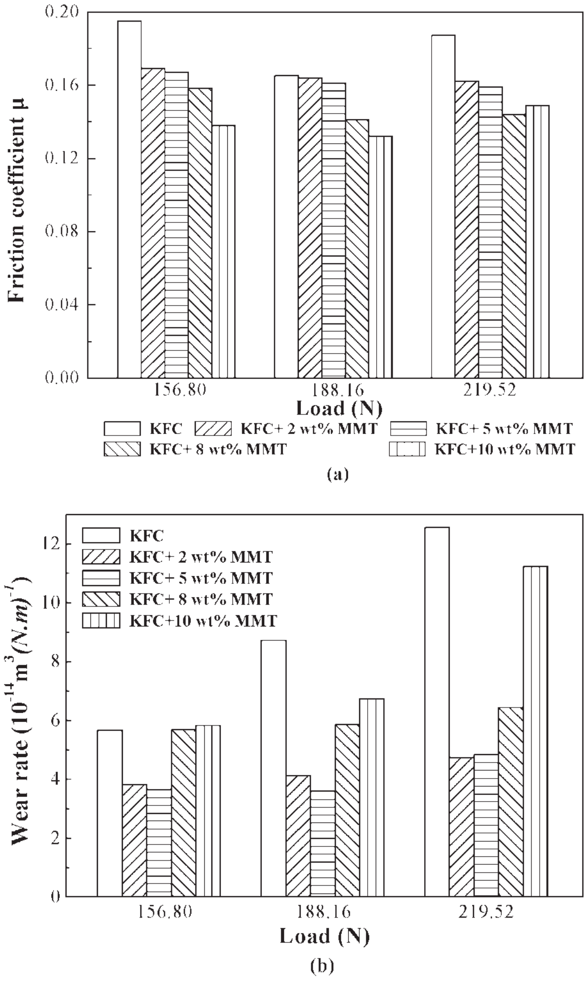


Figure 2 Variation of (a) the friction coefficient and (b) wear rate with the load for KFCs filled with different MMT contents (0.26 m/s).

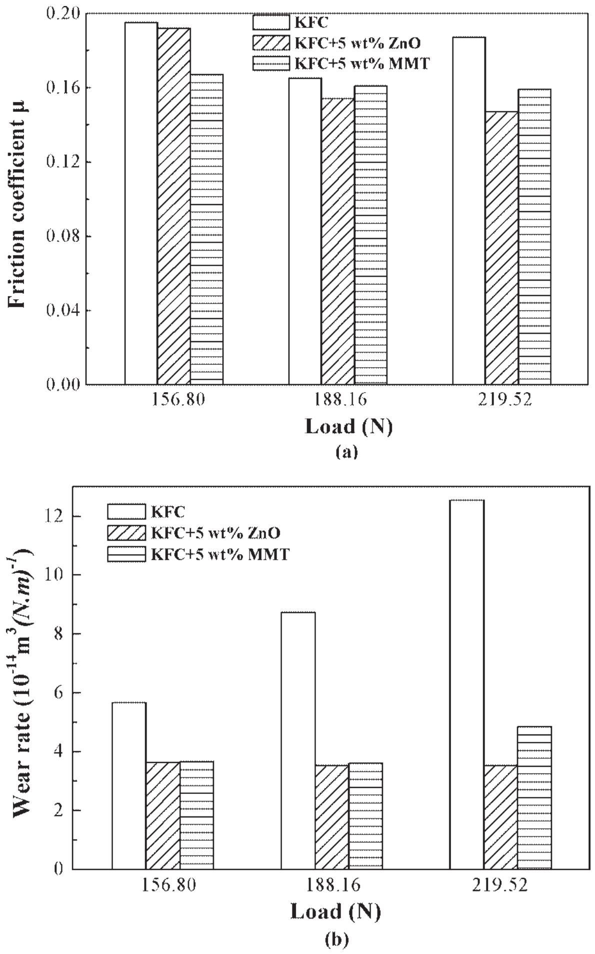


Figure 3 Variation of (a) the friction coefficient and (b) wear rate with the load for three KFCs (0.26 m/s).

of the load. Under different load conditions, adding 5% ZnO or 5% MMT can reduce the friction coefficient and wear rate of the KFCs. The KFCs filled with 5 wt % ZnO have the best antifriction and antiwear properties.

In Figure 4, the typical variations of the frictional coefficient against the sliding time for the unfilled KFCs and those filled with 5 wt % ZnO or 5 wt % MMT at 188.16 N are shown. In three abrasive processes, the steady stage of friction and wear follows the running-in stage. The friction coefficient of the steady stage is lower than that of the running-in stage and is almost independent of the sliding duration. Both ZnO and MMT effectively reduce the peak value and the duration of the running-in stage, which contributes to the continuous transfer film formed on the counterpart surface and results in a lower friction coefficient. In comparison with the steady stage caused by MMT, the steady stage caused by ZnO is smoother, so the composites filled with ZnO achieve the best antifriction and antiwear abilities.

Analysis of the worn surface and counterpart surface

Figure 5 shows micrographs of the counterpart surfaces of three different composites at 188.16 N to illustrate the different antiwear mechanisms of these three composites. This study shows that the tribological behavior of nanoparticle-filled composites is controlled by the transfer film formed on the counterpart surface. It can be seen from Figure 5(a) that the transfer film of the unfilled KFCs scarcely exists on the counterpart surface, and the counterpart surface appears to be rough. Apparent grooves parallel to the sliding direction are formed on the counterpart surface. The material that scales off from the composite surface does not adhere to the counterpart surface and is steadily thrown out of the contact system. As a result of this, uniform coverage of the transfer film on the pin cannot develop, so the protection from the transfer film does not exist anymore, and this corresponds to the worst antiwear property of the unfilled KFCs.

MMT may improve the tribological properties of composites because of its large aspect ratio and surface area and high interfacial activity. In friction, composites are continuously transferred to the counterpart surface until a steady-state thickness of the

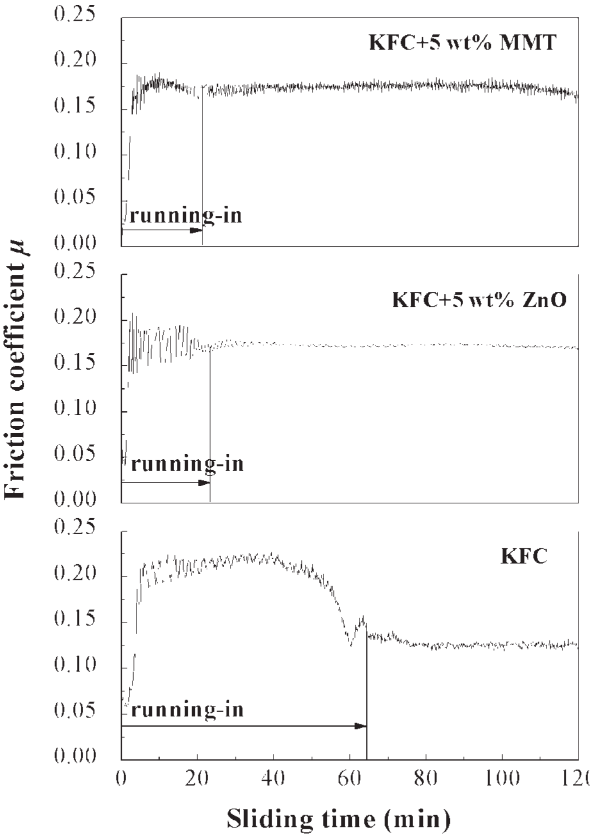


Figure 4 Typical variation of the friction coefficient against the sliding time for three different KFCs (188.16 N, 0.26 m/s).

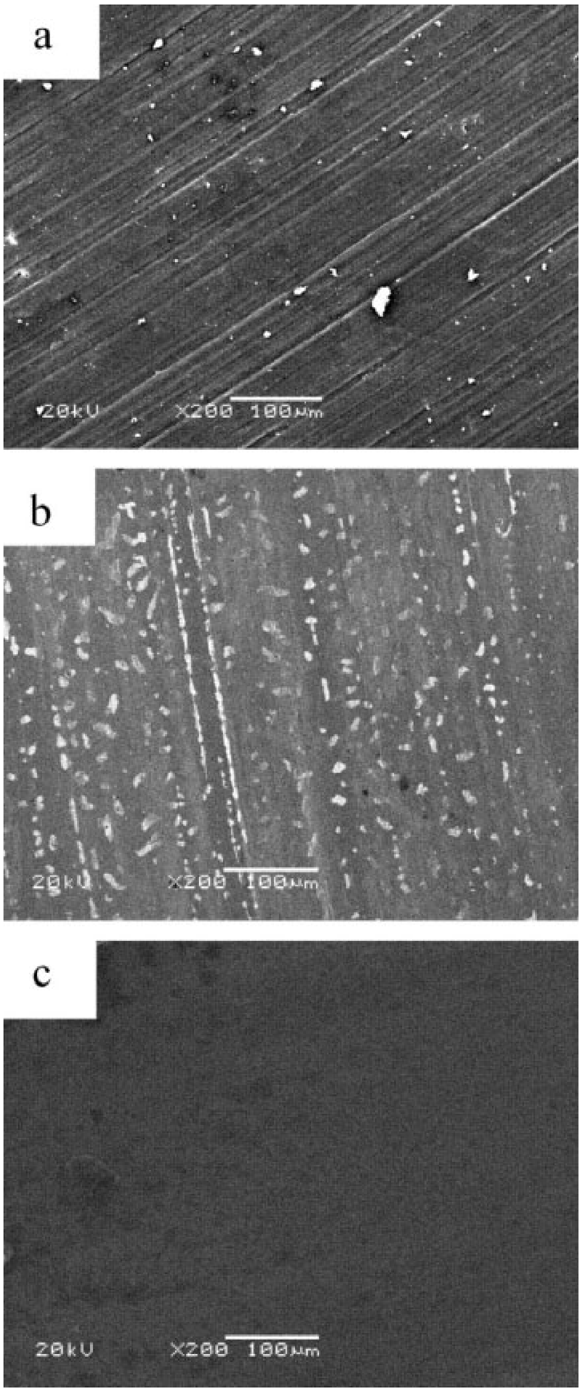


Figure 5 SEM images of counterpart surfaces of (a) KFC, (b) KFC plus 5 wt % MMT, and (c) KFC plus 5 wt % ZnO (188.16 N, 0.26 m/s, 2 h).

transfer film is developed. The thickness, continuity, uniformity, and stability of the transfer film affect the friction and wear behavior of the composites strongly. The transfer film of the KFCs filled with 5 wt % MMT [Fig. 5(b)] appears thin and uniform but not very smooth. The image indicates that MMT nanoparticles can easily transfer with the matrix to the counterpart pin and embed on the transfer film. The high interfacial activity of MMT and the uniformly distributed MMT in the transfer film strengthen the bond between the transfer film and counterpart surface, which is able to keep the hard asperity from damaging the composites. There are enrichment areas of MMT dispersed uniformly on the counterpart surface, which results in the transfer film being not very smooth. Moreover, some mild grooves parallel to the sliding direction are formed on the counterpart surface, so the tribological properties of the composites filled with MMT are worse than those of the composites filled with ZnO at this applied load.

The transfer film of KFCs filled with 5 wt % ZnO [Fig. 5(c)] appears to be thin, very smooth, and coherent, and this promises to provide the best antiwear property for the composites. The main reasons for the improvement of the composites are expected to be the large specific surface area and surface activity of ZnO nanoparticles as well as the uniform dispersion in the matrix and strong combination with the matrix. The nanoparticles are able to carry the applied load because of the strong adhesion. The transfer film can be strengthened because ZnO nanoparticles have the ability to blend well with the wear particles transferred to the counterpart surface. The continuous transfer film can effectively reduce the direct contact between the composites and metallic counterpart surface. As a result, the subsurface stress of the composites can be maintained at lower values, and thus a lower friction coefficient and wear rate are achieved. The various characteristics of the transfer film on the counterpart surfaces also account for the differences in the friction and wear behaviors of the three different composites.

To understand the effects of nanoparticles on the friction and wear behaviors of KFCs filled with nanoparticles, the worn surfaces of three KFCs were also studied with scanning electron microscopy (SEM; Fig. 6). It can be seen that the unfilled KFCs after sliding are characterized by many pulled-out and fractured Kevlar fibers and are seriously damaged [Fig. 6(a)]; this indicates that the composites are subjected to greater contact stress and experience severe peeling. The worn surface of KFCs filled with 5 wt % MMT or 5 wt % ZnO after sliding is relatively regular [Fig. 6(b,c)]. There are fewer Kevlar fibers pulled out and cut from the composites on the worn surface. This is in agreement with the highest antiwear and antifriction abilities of the KFCs filled with 5 wt % MMT or 5 wt % ZnO. The results indicate that adding MMT or ZnO nanoparticles can obstruct the process that causes the transition to severe wear in the unfilled KFCs.

Figure 7 shows the micrographs of the counterpart surface of the KFCs filled with 10 wt % MMT and 10 wt % ZnO at 188.16 N. The transfer film of the KFCs filled with 10 wt % MMT is loose and thick

[Fig. 7(a)]. There are obvious ploughed marks and a discrete distribution of aggregated nanoparticles in the transfer film. For the transfer film of the KFCs filled with 10 wt % ZnO [Fig. 7(b)], the thickness is inconsistent. Moreover, some obvious plucked marks can be seen from the transfer film. This is because excessive fillers tend to conglomerate and lead to less uniformity of the composite system. The surface of the composites is destroyed and transferred to the counterpart surface and then scaled off during the friction process. The bond between the transfer film and counterpart face is weak. The results indicate that the tribological behavior of the KFCs filled with nanoparticles depends on the dispersion of nanoparticles and the adhesion between the transfer film and counterpart surface.

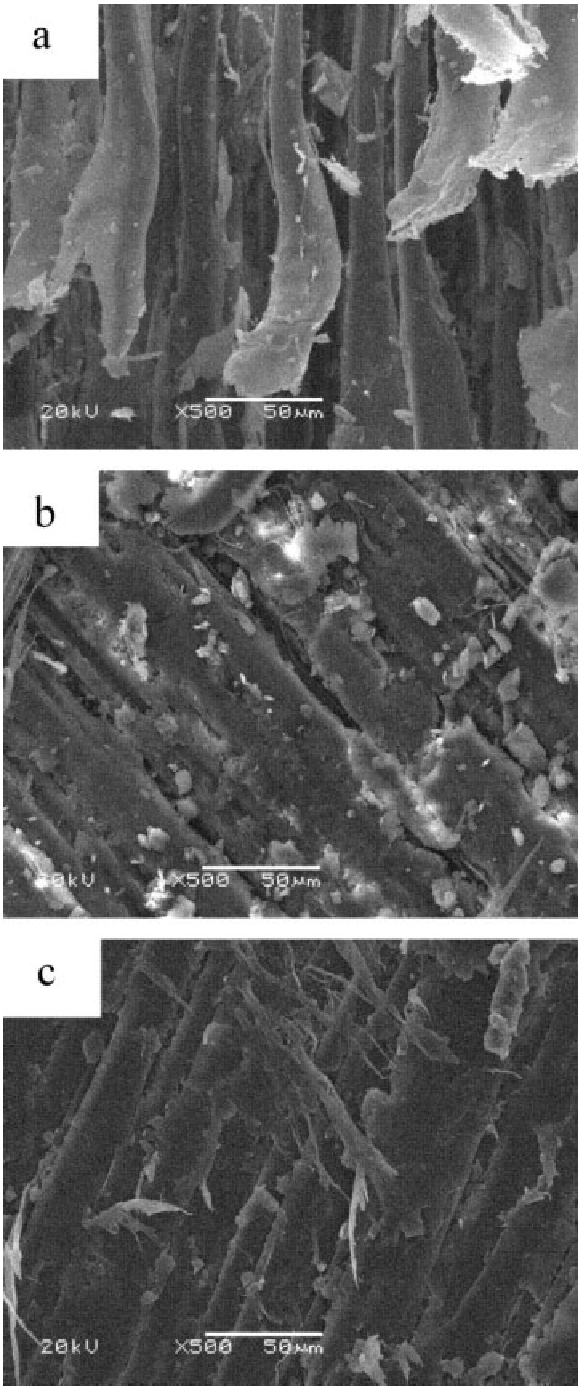


Figure 6 SEM images of worn surfaces of (a) KFC, (b) KFC plus 5 wt % MMT, and (c) KFC plus 5 wt % ZnO (188.16 N, 0.26 m/s, 2 h).

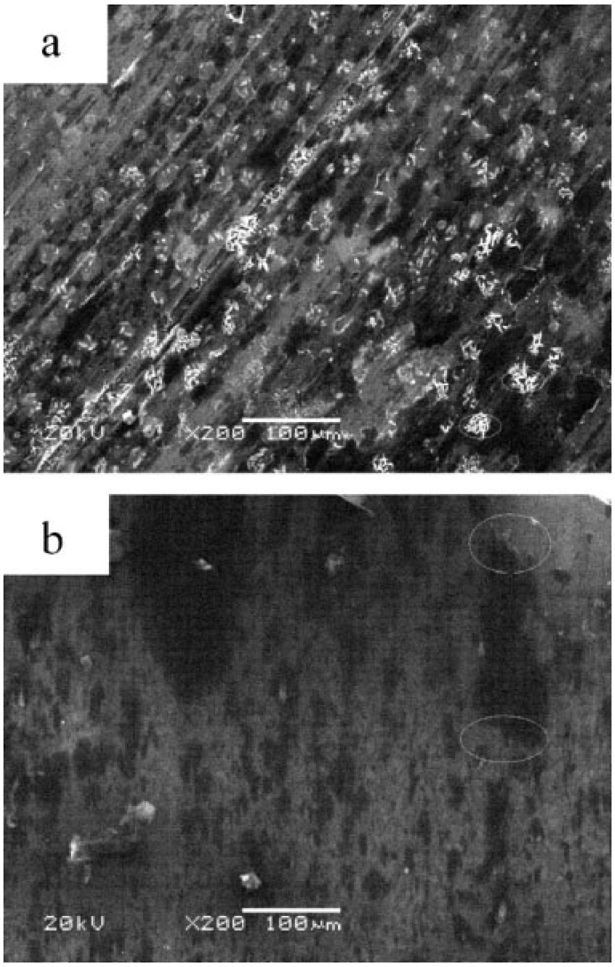


Figure 7 SEM images of counterpart surfaces of (a) KFC plus 10 wt % MMT and (b) KFC plus 10 wt % ZnO (188.16 N, 0.26 m/s, 2 h).

CONCLUSIONS

Adding ZnO or MMT nanoparticles can reduce the destruction and improve the tribological behavior of KFCs. The tribological behavior depends on the content and distribution of nanoparticles and is best when composites contain 5 wt % ZnO or 5 wt % MMT. The transfer film of KFCs filled with 5 wt % ZnO or 5 wt % MMT is thin and relatively smooth, whereas the transfer film of composites filled with 10 wt % ZnO or 10 wt % MMT is thick and discrete and contains a large amount of aggregated nanoparticles.

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