Wear Properties and Mechanisms of Nylon and Carbon-Fiber-Reinforced Nylon in Dry and Wet Conditions

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ABSTRACT: A microinjection machine was used to prepare specimens of nylon 1010 and carbon fiber (CF)-reinforced nylon 1010 composites. The friction and wear properties were investigated with a ring–block wear tester in wet and dry conditions. The wear rate of nylon 1010 increased, but the friction coefficient decreased in water in comparison to that in dry sliding. The wear resistance of CF–nylon increased remarkably by two orders of magnitude due to the reinforcement of the CF. The minimum wear rate was obtained with a 20 vol % content of CF filled in nylon in wet lubrication. The wear rate of CF–nylon in dry sliding friction was as much as approximately eight times, and the friction coefficient decreased to approximately half its value compared with that in water under a load of 200 N. The morphologies and the wear mechanisms of worn surfaces were also examined with Fourier transform infrared spectroscopy and scanning electron microscopy. The results show that the hydrolization of amide groups and the resulting decrease in hydrogen bonds between the molecules of nylon 1010 were important factors that led to a high wear rate of nylon in water. We concluded that the fiber, protruding out of the rubbing surface and carrying the main load between the contacting surfaces, held up the swelling properties and improved the mechanical strength of nylon, which would account for the evident reduction of wear in the nylon composites. © 2004 Wiley Periodicals, Inc. J Appl Polym Sci 93: 789–795, 2004

Key words: nylon; fibers; composites

INTRODUCTION

Nylon is a good bearing material because of its high strength and good wear resistance, so many studies on the friction and wear of nylon composites have been reported, and these composites have been successfully used in many fields.[1–3] Most investigations have focused on the tribological properties of polymers in dry conditions. However, few researchers have studied the tribological performance of polymers in water.[4–7] Watanabe[8] and Zhongqian et al.[9] pointed out that many polymers showed higher wear in water than in air and that the extent of wear of polytetrafluoroethylene (PTFE) composites filled with glass fibers was much greater than that of other polymer composites in water. Lancaster[6] reported that water inhibited the formation of transfer films of carbon–polymer debris on the counterface and that the wear rates were greater those obtained in dry conditions. However, there has been little information available on the tribological properties of nylon and its composites in water until now.

The scope of this study included the investigation of the tribological behaviors and wear mechanisms of nylon 1010 and its composites filled with carbon fiber (CF) in water and in dry conditions. Our aim was to provide some practical guidance for the use of nylon composites in wetting fields.

EXPERIMENTAL

The polymer material used in this study was nylon 1010 in powder form (<175 μm). The chopped type of fiber was high strength, polyacrylonitrile (PAN)-based CF, which was 7 μm in diameter and 60–100 μm long. CF was oxidized for 2 h in a 60% HNO_3 solution, washed with distilled water at 100°C, and dried in a vacuum oven at 120°C before the polymer composites were prepared. Various proportions of the fiber and the dried nylon 1010 (in volume) were mixed mechanically by a steel vane at a temperature of 210–220°C in a microinjection machine (WZM-I; Jilin University, China), and the prepared specimens were 6 × 10 × 20 mm.

To investigate the heat history and changes in molecular structure, we used differential scanning calorimetry by heating the nylon and CF–nylon specimens. Thermal conductivity measurements were made on a guarded heat flow meter (TCA 446, Netzsch, Germany). The physical and mechanical

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TABLE I
Properties of Nylon and CF–Nylon

Property	Nylon	10% CF–nylon	20% CF–nylon
Specific gravity (g/cm^3)	1.05	1.12	1.20
Hardness	40.5	65.0	74.0
Tensile strength (MPa)	49.2	71.0	82.0
Melting point (°C)	204.2	204.3	204.5
Thermal conductivity (W/m K)	0.23	0.38	0.95

properties of the nylon and CF–nylon used in this study are shown in Table I.

Friction and wear experiments were run in a ring–block wear tester (MM-200, Shanghai University, China) at room temperature in an ambient atmosphere at a velocity of 0.42 m/s under normal loads from 50 to 400 N. Distilled water was added to the rubbing surface at a rate of 40–50 drops/min during testing. The block specimen and the steel ring (AISI 1045; Shanghai Baosteel Corp., China) were ground with 600-grade SiC paper, which provided surface roughnesses of 0.4–0.6 and 0.10–0.15 μm, respectively. Before each test was started, the surfaces of the block and the steel ring were cleaned with soft paper soaked in acetone and dried. Each friction and wear test was performed for 2 h. After the test was finished, the block specimen was dried in a vacuum oven at 110°C for 2 h and was then placed in a vacuum desiccator for measurement. The weight loss of the block was measured to an accuracy of 0.01 mg. The friction force was measured from the output of a strain mounted on a vertical arm that carried the block. Each sliding test was repeated three times, and the plotting values were the mean of the three experimental values. The maximum variation between these experimental values was not higher than ±15%. The worn surfaces of the nylon matrix and its composites were studied by scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

Friction and wear of nylon 1010

The variations of the friction coefficient and the wear rate with loads for nylon under the two environments are shown in Figures 1 and 2, respectively. As shown in Figure 1, the friction coefficient of nylon decreased from 0.3 to 0.18 in water but increased from 0.45 to 0.75 in the dry condition when the load was changed from 50 to 200 N. Compared to the dry condition, the friction coefficient decreased by 1.5–3.8 times in water. The results shown in Figure 2 show that the wear rate of nylon increased with increasing load. The wear rate of nylon in water was about three to five times that in dry sliding under loads of 50, 100, and 150 N. However, the nylon block was intensely worn when the load was increased to 200 N in the dry condition. The temperature of the nylon surface increased because of the accumulation of frictional heat under high compressive stresses, which resulted in the rapid increase of the adhesive friction. Most of the frictional quantity of heat could be dissipated by the distilled water; also, water can be used as a kind of polar lubricant and could reduce the direct contact zone of the nylon block with the counterface surface. Therefore, the friction of nylon in water was lower than that in dry sliding. Moreover, the absorption of water by nylon could lead to a variety of effects, including (1) a reduction in the strength of the nylon and an increase in the elongation at break, (2) an inhibition of the formation of transfer films of nylon debris on the counterface, and (3) an increase in the chemical corrosion wear, which would lead to wear rates of nylon greater than those obtained in dry sliding.

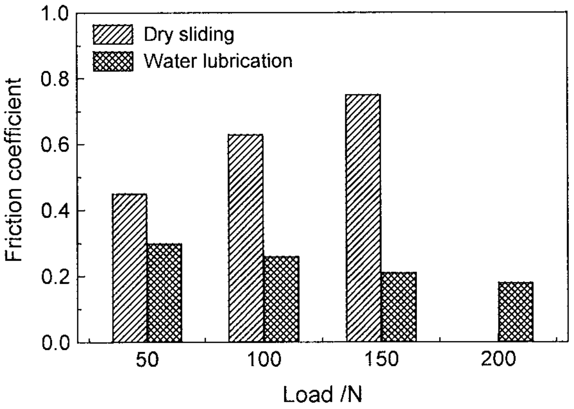


Figure 1 Effect of load on the friction coefficient of nylon in wet and dry conditions.

Wear mechanisms of nylon 1010

Figure 3 shows the SEM micrographs of the worn surface of nylon 1010 under a load of 200 N in the two

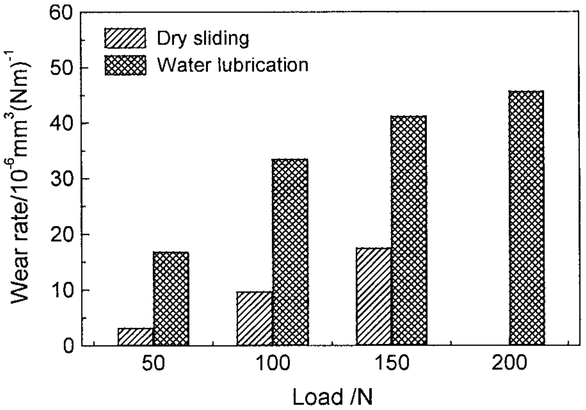
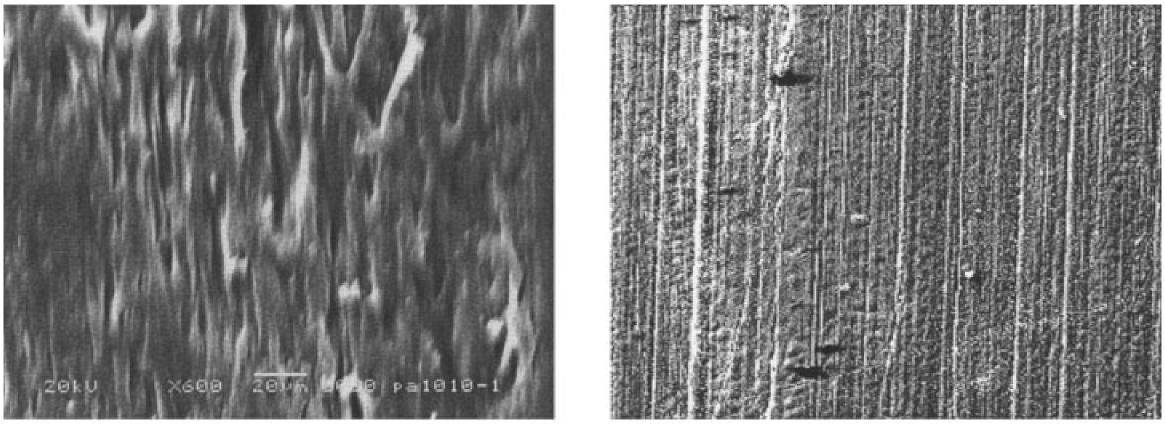


Figure 2 Effect of load on the wear rate of nylon in wet and dry conditions.



(a) (b)

Figure 3 SEM micrographs of the worn surfaces of nylon 1010 under a load of 200 N in (a) dry and (b) wet conditions (600×).

environments. The rubbing surface of nylon was coarse, and a flowing track existed that was parallel to the sliding direction in the dry condition [Fig. 3(a)]. The wear debris of nylon found in the experiments was not like small particles but instead was in the form of large slices after 30–35 min, and the nylon matrix was flowed and extruded from the frictional surface under high loads. Figure 3(b) shows that ploughed marks and small peeling pits appeared on the rubbing surface of nylon in water, and the main wear mechanisms of the nylon matrix were microcutting and microploughing caused by the asperities of the counterface surface, possibly accompanied by fatigue wear or erosive wear.

Fourier transform infrared (FTIR) spectroscopy was used to analyze the wear mechanisms of the worn surface of nylon in water lubrication (Fig. 4). There was no evident difference in most of the peaks between the two curves for the unrubbed surface of nylon and the worn surface of nylon in water. However, the typical peak at 3304.89 cm^{-1} for the nylon surface had displacements of approximately 10 cm^{-1} in water compared to the peak at 3314.67 cm^{-1} for the unrubbed nylon. This peak corresponded to the flex oscillation of N—H bonds; also, it was sensitive to the hydrogen bonds between the surface molecules of nylon. The previously discussed experimental results show that part of the amide groups were hydrolized and that the extent of hydrogen bonding decreased during sliding in water. This led to a decrease in the mechanical strength and wear resistance of nylon. Moreover, water could diffuse into the nylon matrix from macrocracks and micropores in the polymer surface, which resulted in the swelling of the polymer surface and the destruction of the interface of the polymer. As a result, the physical and chemical effects intensified the increasing wear rate of nylon in water.

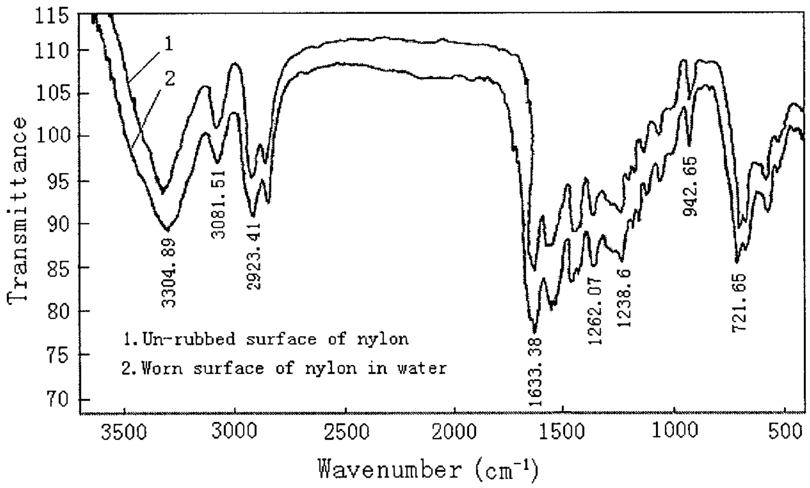


Figure 4 FTIR spectra for the unrubbed surface of nylon and the worn surface of nylon in water.

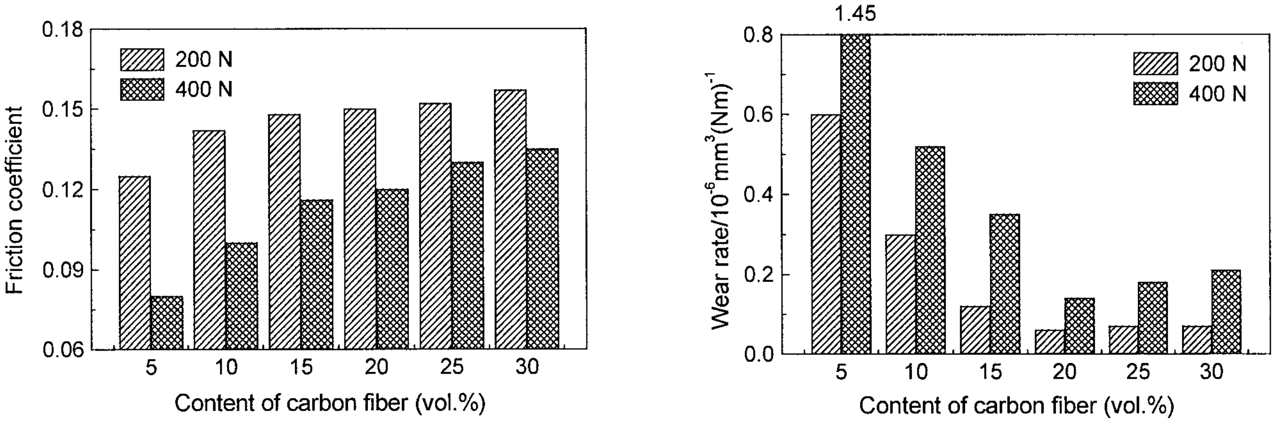
TABLE II
Friction Coefficients and the Wear Rates of Nylon Composites Under 200-N Loads

Material	Environment	Friction coefficient	Wear rate [10^{-6} mm^3 (N m)$^{-1}$]	Load (N)
Nylon 1010	Dry	0.70	Intensely worn	200
	Wet	0.18	45.8	
		0.26	2.56	200
10% CF–nylon	Dry	0.25	4.65	300
	Wet	0.14	0.32	200
		0.10	0.52	400

CF-reinforced nylon 1010 composites

Table II gives the test results of the tribological properties of nylon and 10% CF–nylon in the wet and dry conditions. The wear rate and friction coefficient of nylon was reduced by the addition of CF; the wear resistance of 10% CF–nylon increased by two orders of magnitude, and the friction coefficient decreased to 77% of that of pure nylon in water under a 200-N load. This was attributed to the lubricating action of the CFs, so the tangential stresses causing shear deformation were lower. The reduced wear of the composites could have also been caused by fibers providing strength to the polymer matrix and protruding out of the rubbing surface during sliding.[10] The wear rate of 10% CF–nylon increased, and the friction coefficient decreased slightly with increasing load under the two environmental conditions. Meanwhile, the friction coefficient and the wear rate of the nylon composites in water were lower than those in dry sliding; that is, the wear resistance of 10% CF–nylon increased as much as approximately eight times and the fiction coefficient decreased to 54% of those values in dry sliding under a load of 200 N. The wear rate of 10% CF–nylon increased rapidly as the load was increased from 200 to 300 N, and the composite was intensively worn under a load of 400 N in the dry condition. However, 10% CF–nylon had good wear resistance and a low friction coefficient under a 400-N load in water lubrication. From these experiments, we concluded that pure nylon did not have good thermomechanical resistance. Fiber-filled polymers had higher thermal conductivities and improved the dissipation of accumulated frictional heat. Also, water was used as a kind of polar lubricant in this work and synergistically enhanced the process of dissipation; therefore, the wear resistance of CF–nylon was remarkably improved in water lubrication.

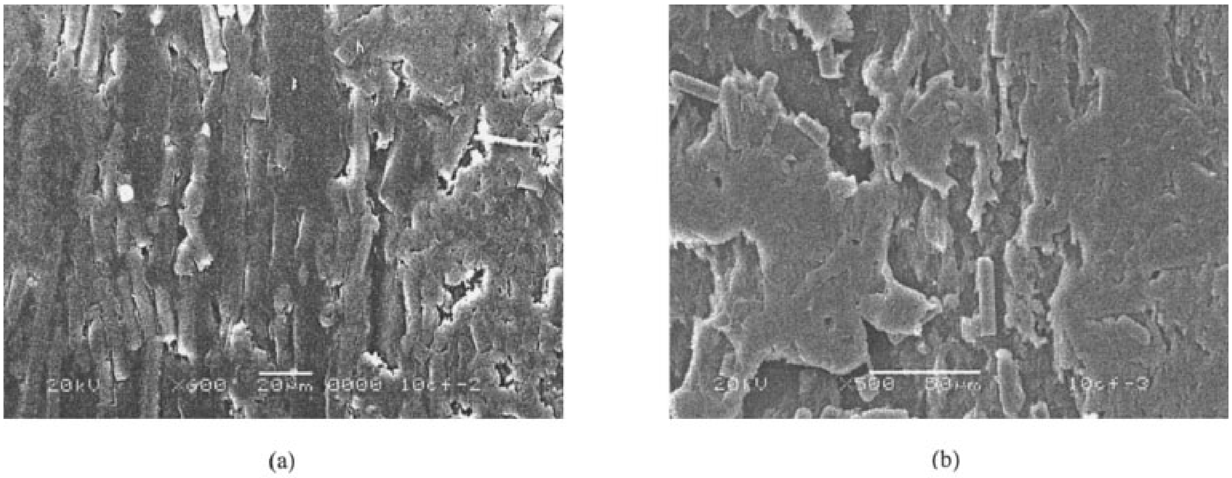
Because of these results, we decided to fill various proportions of CF in nylon, hoping to further improve the tribological properties and gain the best wear resistance for the composites in water testing. The variation of the tribological properties for these composites is given in Figure 5 for loads of 200 and 400 N. As shown in Figure 5(a), the friction coefficient of the nylon composites decreased with increasing load. The friction coefficient increased rapidly with increasing volume content of CF from 5 to 15% and then increased slowly when the fiber content was higher than 15%. In particular, the friction coefficients of the composites were almost steady under a load of 200 N. The



(a)

(b)

Figure 5 Variation of the (a) friction coefficient and (b) wear rate of nylon reinforced with various volume contents of CF under different loads in water lubrication.



(a) (b)

Figure 6 SEM micrographs of the worn surfaces of 10% CF–nylon in the dry condition under loads of (a) 200 and (b) 300 N.

lowest friction coefficient of 5% CF–nylon (which was 0.08) in this experiment was obtained under a load of 400 N. This indicated that the lower amount of CF was more effective in reducing the friction of the composites in water lubrication. As shown in Figure 5(b), the wear rate increased with increasing load. The wear rate decreased distinctly with a content of CF ranging from 5 to 20% and then slightly increased when the fiber content was higher than 25%. As a result, the wear rate was at a minimum for the 20% CF-filled nylon composite [which was 1.4×10^{-7} mm^3 (N m)$^{-1}$] under a load of 400 N. Selective proportion content for good wear resistance of fiber-reinforced polymer composites has been pointed out by other studies.[10–12] It has been proven that the presence of an excessive amount of fiber in polymers, which partially scrape the transfer films, or of inadequate bonding between the fibers and polymers causes the production of composites with low strengths.

Figure 6 shows the SEM micrographs of the rubbed surfaces of the CF-reinforced nylon composites in dry sliding friction. As shown in Figure 6(a), ploughed marks appeared on the rubbing surface of the composite under a load of 200 N. Fibers seemed to protrude out of the rubbing surface, indicating that a major share of the normal load was supported by the fibers, which accounted for the reduction in the wear rate. The worn surface was deformed and the fibers were torn from the nylon matrix when the load was 300 N [Fig. 6(b)]. Extensive fragmentation indicated that the adhesive strength between the fiber ends and the nylon became weak when high frictional heat accumulated in the contacting surface.

Figure 7 shows the SEM micrographs of the rubbed surfaces of the CF-reinforced nylon composites in water lubrication. As shown in Figure 7(a), slightly ploughed tracks appeared on the rubbed surface of 10% CF–nylon under a load of 200 N. The wear of the nylon matrix was accompanied by the sliding wear of the fibers, that is, by thinning and rubdown. The wear debris was in the form of fine particles, still mainly held loosely to the fiber tips, which indicated slight wear in the sliding process. Figure 7(b) shows several fiber–matrix and matrix–matrix cracks on the rubbing surface of 10% CF–nylon under a high load of 400 N. We attributed this to subsurface deformation during sliding, which led to crack nucleation at the fiber–matrix interface and crack propagation parallel to the surface at a depth, dependent on the influence of the high friction force and water swelling. Figure 7(c,d) shows the worn surface rubbing against the steel counterface by the 20% CF–nylon composite. Unlike in the case of the 10% CF–nylon fiber reinforcement, the worn surface of the composite revealed no evident marks of microcutting and microploughing wear and not much wear-particle accumulation [Fig. 7(c)]. The reason for this could have been the presence of a high amount of fiber in the nylon, which would have increased the mechanical strength and decreased the shear deformation of the composite surface. As shown in Figure 7(d), the worn surface of 20% CF–nylon had a slightly ploughed appearance under an increased load of 400 N. The CFs were also rubbed and damaged. The surface features here were different from those observed in earlier work in dry conditions,[10,11,13] where the worn surface was severely ploughed and deformed. Comparatively, the worn surfaces were almost smooth and slightly ploughed even in a high load under water action.

From the SEM micrographs in Figure 7, we found that no peeling pits existed in the worn matrices of the nylon composites compared to that of pure ny-

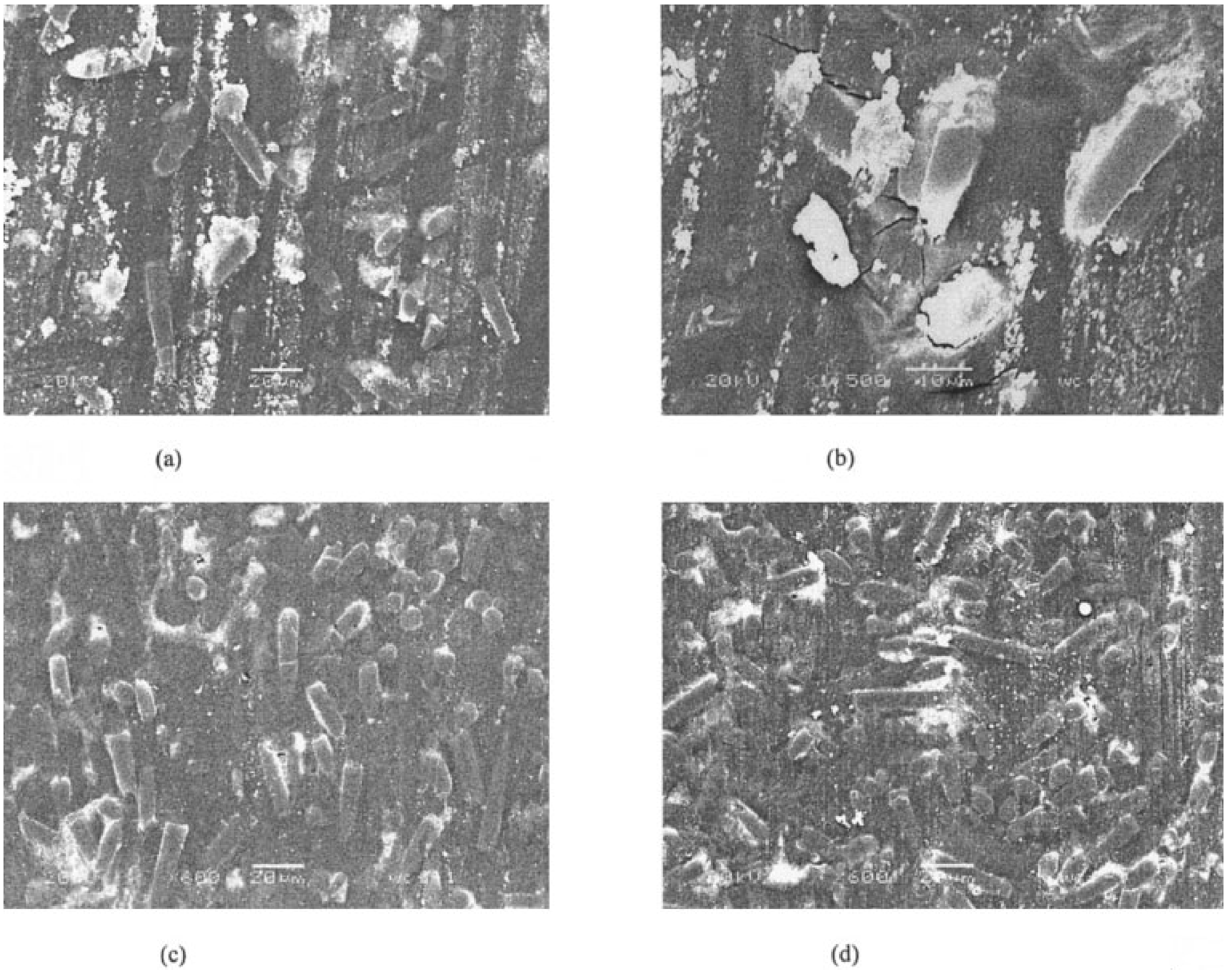


Figure 7 SEM micrographs of the worn surfaces of the CF-reinforced nylon composites in water lubrication under different loads: (a) 10% CF–nylon and a 200-N load, (b) 10% CF–nylon and a 400-N load, (c) 20% CF–nylon and a 200-N load, and (d) 20% CF–nylon and a 400-N load.

lon. The CF could have held up the swelling properties and improved the hardness and mechanical strength of the nylon. In addition, it is known that a layer of lubricating water film can easily form on the counterface surface; thus, the lubricating condition of the frictional surface could have been greatly improved, adding to the synergistic action of CF and leading to the obvious reduction in the wear rate of the CF–nylon composites. We concluded from these results that CF–nylon has good tribological properties and could be used in practice in water environments.

CONCLUSIONS

1. The friction coefficient of nylon 1010 was lower in water lubrication and the wear rate was higher than in dry sliding when the load was changed from 50 to 150 N.
2. Part of the amide groups were hydrolyzed and hydrogen bonds decreased between the surface molecules of nylon in water. This led to a decrease in the mechanical strength and wear resistance of nylon.
3. The tribological and mechanical properties of nylon were remarkably improved by the addition of CFs. The wear resistance of 10% CF–nylon was increased by two orders of magnitude compared to that of pure nylon in water under a load of 200 N.
4. The wear resistance of 10% CF–nylon in water increased as much as approximately eight times and the friction coefficient decreased to 54% of those values in dry sliding under a load of 200 N.
5. A lower amount of CF was more effective in reducing the friction of composites, and the wear rate was at a minimum for the 20% CF-filled nylon composite [which was 1.4×10^{-7} mm^3 (N m)$^{-1}$] under a load of 400 N.

6. The CF–nylon had excellent wear-reducing properties and a low friction coefficient in water lubrication, so this nylon composite would be a good selection for use in wetting conveying fields.

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