A Study of Tribological and Mechanical Properties of PTFE Composites Filled with Surface Treated $K_2Ti_6O_{13}$ Whisker

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ABSTRACT: $K_2Ti_6O_{13}$ whisker was modified with *n*-octadecyltrichlorosilane (OTS), fluorosurfactant (FSK), and silane coupling agent (KH-550), respectively. The surface energy of $K_2Ti_6O_{13}$ whisker was calculated based on Van Oss-Chaudhury-Good function. Then the influence of surface modification on the tribological and mechanical properties of $K_2Ti_6O_{13}$ whisker filled polytetrafluoroethylene (PTFE) composites was studied. Surface energy calculation shows that the surface energy of OTS-treated $K_2Ti_6O_{13}$ whisker is only 29.0 mJ/m^2, which is the closest to the value of pure PTFE. Among all samples, the PTFE composite filled with OTS-treated $K_2Ti_6O_{13}$ whisker shows the best antiwear property, tensile strength, and impact strength, which is about 19 to 33%, 15 and 55% higher than that of untreated $K_2Ti_6O_{13}$ whisker filled PTFE, respectively. J Appl Polym Sci 124: 1456–1463, 2012

Key words: composites; mechanical properties; PTFE

INTRODUCTION

Polytetrafluoroethylene (PTFE) is an excellent solid lubricant and has been used commonly in bearing and seals applications.[1] However, PTFE exhibits high wear rate at normal friction conditions. Thus a lot of efforts have been continuously made to decrease the wear of PTFE by means of inorganic or organic compound inclusion.[2–4]

Among the numerous inorganic fillers, $K_2Ti_6O_{13}$ whisker has been found to be a promising reinforcer for the wear-resistant composites due to its unique properties such as outstanding mechanical performance, low hardness (Mohs hardness is 4), and excellent chemical stability.[5] The tensile strength and modulus of elasticity are 7 and 280 GPa for $K_2Ti_6O_{13}$ whisker while those for carbon fibers are only 3.1 and 230 GPa.[6] One of the advantages of $K_2Ti_6O_{13}$ whisker is that $K_2Ti_6O_{13}$ whisker is a kind of very fine microreinforcing material (about several hundred nanometer in diameter), which ensures it to be suitable for reinforcing the very narrow space in composites that conventional micrometer fillers are unable to do.[7] In practice, it is suitable for making products that have a complex shape, great precision, and high polished surface.[5]

It is well known that the smaller the size of filler particles is, the larger their specific surface area becomes, and the more likely the particles will agglomerate.[8] Thus, $K_2Ti_6O_{13}$ whisker is easily agglomerated before any surface treatment. On the other hand, $K_2Ti_6O_{13}$ whisker belongs to inorganic ceramic, whose surface energy is very high. However, PTFE is a typical polymer with an ultralow surface energy.[9] The huge difference of surface energy between $K_2Ti_6O_{13}$ whisker and PTFE leads to the inferior interfacial compatibility, which directly results in the poor performance of the composites.

Therefore, pretreatment of $K_2Ti_6O_{13}$ whisker before experiment is practically essential. Selective surface modification techniques have been the focus of research and technology for a variety of applications, including sorption and separation media, wetting and adhesion, lubricants, pigments, sensors, and optical and electronic devices.[10–13] Functional organosilanes of the general formula R_nSiX_{4-n} ($n = 0$–3), where X is a readily hydrolyzable group (most often chloro or alkoxy), are widely used as effective surface modifying agents for different substrates.[14] Recently, self-assembled monolayers (SAMs) have been the powerful tools to investigate specific properties in

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surface science.[15] *n*-Octadecyltrichlorosilane (OTS) is widely used as SAMs to control the surface energy of inorganic materials.[16]

In this work, $K_2Ti_6O_{13}$ whisker is treated with silane coupling agent (KH-550), *n*-octadecyltrichlorosilane (OTS), and fluorosurfactant (FSK) to improve the properties of $K_2Ti_6O_{13}$ whisker filled PTFE. The purpose of this work is to study the effect of surface modification on the tribological and mechanical properties of PTFE composites filled with surface modified $K_2Ti_6O_{13}$ whisker. Some insights into the tribological and mechanical mechanisms of the PTFE composite are also proposed.

EXPERIMENT

Materials

In the experiments, the powder of PTFE with an average of 25 μm was supplied by Dupont (7A-J, commercial product). $K_2Ti_6O_{13}$ whisker was synthesized by calcinating the mixture of K_2CO_3 and TiO_2 in our laboratory. The method of producing $K_2Ti_6O_{13}$ whisker was described in our previous work.[17] The main reactions can be described as follows:

$$K_2CO_3 + nTiO_2 \overset{1000-1150^\circ C}{\longrightarrow} K_2Ti_4O_9\ (w)\ + CO_2 \quad (1)$$

$$K_2Ti_4O_9\ (w)\ + H^+ \overset{pH=9.2}{\longrightarrow} K_2Ti_6O_{13}\ (w)\ + K^+ + H_2O \quad (2)$$

where (w) represents whisker.

Three types of surface modifiers (as shown in Fig. 1) were used to pretreat $K_2Ti_6O_{13}$ whisker. *n*-Octadecyltrichlorosilane (OTS, 95%) was supplied by Acros Organics. Silane coupling agent (KH-550) was bought from Nanjing Shuguang Chemical Factory (China). Fluorosurfactant (FSK) was obtained by Zhejiang Yuanda (China). Acetone, ethanol, heptane, ethylene glycol, and benzene were obtained by Shanghai Chemical Reagent (China).

Surface treatment of $K_2Ti_6O_{13}$ whisker

Treated with OTS

$K_2Ti_6O_{13}$ whisker was dried at 110°C for 12 h and then preserved in a desiccator. Then $K_2Ti_6O_{13}$ whisker was added into a mixture of OTS and heptane (1 : 1000 v/v) and stirred about 2 h until a uniform suspension formed. Then, the suspension was rinsed, and washed with acetone (three times) to remove excess OTS. Finally, the sample was dried at 60°C in a vacuum drying oven for 5 h.

Treated with KH-550 or FSK

$K_2Ti_6O_{13}$ whiskers were dried at 110°C for 12 h and then preserved in a desiccator. Then $K_2Ti_6O_{13}$ whisker

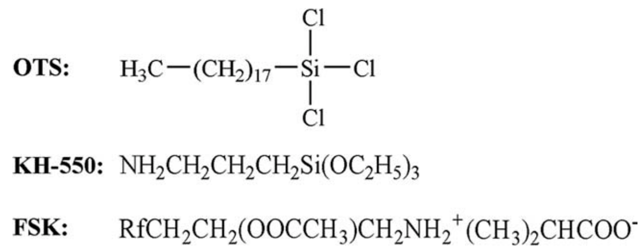

Figure 1 Structure formula of surface modifiers used in this work.

was added into the acetone solution of KH-550 or FSK with thoroughly stirring to form homogenous whisker solution. The content of KH-550 or FSK was 1 wt % with respect to the fiber weight. After that, it was dried at room temperature for 8 h to evaporate the solvent, subsequently dried at 80 to 90°C for 2 h.

In this work, the morphologies of the treated and untreated $K_2Ti_6O_{13}$ whisker were examined by an optical microscope.

FT-IR analysis

To identify the presence of OTS, KH-550, or FSK on the surface of $K_2Ti_6O_{13}$ whisker, FT-IR testing was used. FT-IR spectra were recorded on a Nicolet Nexus B70 spectrometer in the 500 to 4000 cm^{-1} wavenumber range. Sixty-four scans were taken at a resolution of 4 cm^{-1}. For testing, the samples were first ground to powder in an agate mortar and then mixed with KBr at a mass ratio of 1 : 500. A hydraulic press was used to press the resulting mixtures to discs of 10 mm in diameter at 10 MPa for 3 min.

Water contact angle measurement and surface energy calculation

Water contact angle measurement

The static contact angles (CA) of sessile water droplets along the samples were measured with a KRUSS G 10 contact angle instrument. The volume of the water drops was kept at about 5 μL. Each recorded angle was the average of at least six measurements with a typical error of ±2°.

Surface energy calculation

The surface energy of the treated $K_2Ti_6O_{13}$ whisker can be calculated out through Van Oss-Chaudhury-Good function:

$$(1+\cos\theta)\gamma_L = 2\left(\sqrt{\gamma_S^d\gamma_L^d}+\sqrt{\gamma_S^+\gamma_L^-}+\sqrt{\gamma_S^-\gamma_L^+}\right) \quad (3)$$

$$\gamma_S = \gamma_S^d + \gamma_S^p = \gamma_S^d + 2\sqrt{\gamma_S^+\gamma_S^-} \quad (4)$$

where θ is the static contact angles of sessile water, ethylene glycol, and benzene droplets along the

TABLE I
Values of the Surface Tension and Components of Liquids (mJ/m^2 20°C)[18]

Liquid	γ_L	γ_L^d	γ_L^p	γ_L^+	γ_L^-
Benzene	28.9	28.9	0	0	0
Ethylene glycol	48.0	29.0	19.0	1.92	47.0
Water	72.8	21.8	51	25.5	25.5

samples, respectively. γ_L is the liquid's surface energy, while γ_S is the sample's surface energy. γ_S^d and γ_L^d are the liquid's and the sample's dispersion component. γ_S^p is the sample's polarity component. γ_L^+ and γ_S^+ are the liquid's and the sample's Lewis electron-acceptor component. γ_L^- and γ_S^- are the liquid's and the sample's Lewis electron-donor component. The γ_L, γ_L^+, and γ_L^- values of three liquids used in this article are listed in Table I.

Preparation of $K_2Ti_6O_{13}$ whisker filled PTFE composites

The treated $K_2Ti_6O_{13}$ whisker was thoroughly mixed mechanically with the PTFE powder, molded into the blocks by compressing molding under a pressure of 70 MPa for 5 min. In our previous work, it was found that 20 wt % $K_2Ti_6O_{13}$ whisker filled PTFE had better tribological properties.[19] Thus, the fraction of $K_2Ti_6O_{13}$ whisker in each composite studied in this article was set at 20 wt %. After molding, the PTFE composite blocks were sintered at 380°C for 4 h in stove and cooled back to the room temperature at a rate of 40°C/h. At last, the sintered blocks were cut into the shape that is shown in Figure 2(C), which is 26 mm in external diameter, 22 mm in inner diameter, and 2.5 to 3 mm in shoulder height finally.

Friction and wear tests

The friction and wear tests were conducted on a ring-on-ring friction and wear tester. The contact schematic diagram of frictional parts is shown in Figure 2(A). The counter material was a steel ring made from AISI1045 steel (0.42–0.45% C, 0.17–0.37% Si, 0.58–0.80% Mn, P, 0.040%, S, 0.040%) with a hardness of HRC 51. Sliding was performed under dry friction and ambient conditions (temperature: 25°C, humidity: 50 ± 5%) at the sliding velocity of 1.4 m/s, normal loads of 100, 150, or 200 N. The test time was 60 min. The friction force was measured with a torque shaft, provided with strain gauges, and the coefficient of friction was calculated from the friction force. Before each test, the surfaces of each specimen and counterpart ring [36 mm in external diameter and 18 mm in inner diameter and 8 mm in thickness (Fig. 2(B)] were polished with 800 grit paper to a surface roughness of 0.2 to 0.4μm and were cleaned with acetone. At last the wear volume loss was calculated out from the loss of each specimen's weight.

In this work, three replicate friction and wear tests were carried out so as to minimize data scattering, and the average of the three replicate test results was reported.

Tensile tests

The mixture of $K_2Ti_6O_{13}$ whisker and PTFE was molded into the narrow-waisted dumbbell-shaped slab specimens in accordance with ASTM D638-89. The tensile tests were carried out on a Universal Tester (Model CMT5254) at room temperature. The beam rate was at 50 mm/min. All the values were averages of at least five measurements.

Impact tests

The mixture of $K_2Ti_6O_{13}$ whisker and PTFE was molded into the slab specimens with the size of 120 × 15 × 5mm. The impact tests were carried out on an impact test machine (Model XJJ-50). All the values were averages of at least five measurements.

The worn surfaces and impact-fractured surfaces morphologies of the treated- and untreated-$K_2Ti_6O_{13}$ whiske filled PTFE composites were examined with a QUANTA-200 SEM.

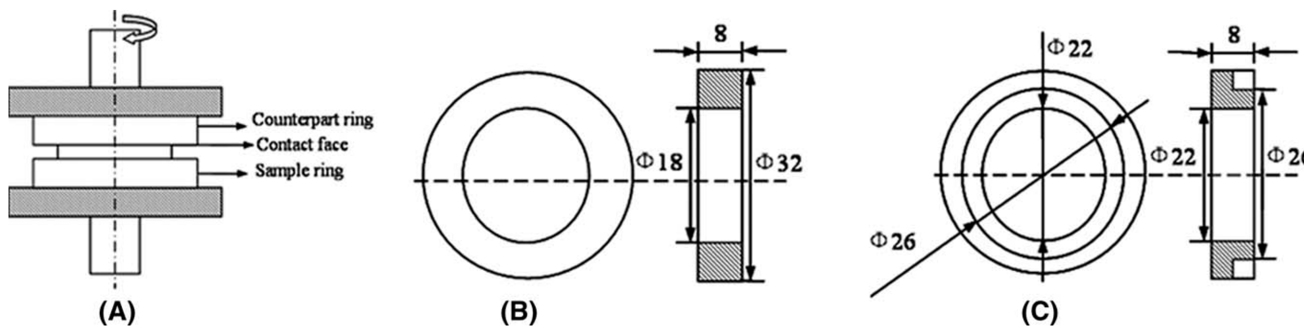

Figure 2 The contact schematic diagram of wear tester, (A) ring on ring contact, (B) counterpart ring, (C) sample ring.

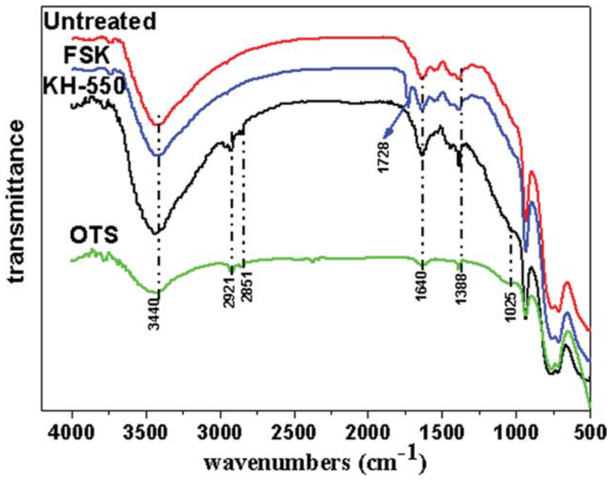

Figure 3 FT-IR spectra of different treated $K_2Ti_6O_{13}$ whisker in the range of 4000 to 500 cm^{-1}. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS AND DISCUSSION

FT-IR analysis the surfaces of surface-treated $K_2Ti_6O_{13}$ whisker

Figure 3 shows the typical FT-IR spectra of surface-treated $K_2Ti_6O_{13}$ whisker. It can be seen from Figure 3 that the untreated $K_2Ti_6O_{13}$ whisker has absorption bands, which are found for all the samples, at around 3440, 1640, 1388 cm^{-1}, and so on. Those at 1640 and 3440 cm^{-1} are likely due to H_2O adsorbed in KBr.[20] Band at 1388 cm^{-1} is attributed to C—O band. However, the effect of adsorbed H_2O on the FT-IR spectra makes it difficult to discriminate the absorption bands of hydroxyl and other groups that contained C—O bands (usually between 1000 and 1400 cm^{-1}).[21]

After FSK treatment, the sample shows absorption band at about 1728 cm^{-1}, which is assigned to the carboxyl group.[21] The sample shows absorption band at about 1025, 2851, and 2921 cm^{-1} when it is treated with the coupling agent KH-550 or OTS. Those at 2851 and 2921 cm^{-1} should be attributed to —CH_2—CH_2— stretching. Band at 1025 cm^{-1} is attributed to Si—O band.[22] It confirms that the sample is coated with FSK, KH-550, or OTS successfully.

Water contact angle of the surface modified $K_2Ti_6O_{13}$ whisker

Table II provides the water contact angle of different surface modified $K_2Ti_6O_{13}$ whisker. The water contact angle of unmodified $K_2Ti_6O_{13}$ whisker is only 5.2°. Generally speaking, the material can be defined as hydrophilic material if its water contact angle is below 90°, otherwise, it is hydrophobic. Obviously, the untreated $K_2Ti_6O_{13}$ whisker is a kind of hydrophilic material. After surface modification, the water contact angle increases dramatically, which indicates that the surface property of $K_2Ti_6O_{13}$ whisker has been changed. After OTS modification, the water contact angle of $K_2Ti_6O_{13}$ whisker increases to 103.5° (change into hydrophobic surface), which is greatly higher than that of KH-550 or FSK-treated $K_2Ti_6O_{13}$ whisker (47.9°, 39.8°). The water contact angle of OTS-treated $K_2Ti_6O_{13}$ whisker is only a little lower than that of pure PTFE (113.6°). The water contact angle difference between PTFE and OTS modified $K_2Ti_6O_{13}$ whisker is the smallest. Thus, it may be inferred that OTS improves the compatibility between PTFE and $K_2Ti_6O_{13}$ whisker.

TABLE III
The Surface Energy of Untreated and Surface Modified $K_2Ti_6O_{13}$ Whisker (mJ/m^2 20°C)

Samples	γ_S	γ_S^d	γ_S^p
Untreated $K_2Ti_6O_{13}$ whisker	69.2	20.1	49.1
FSK-treated $K_2Ti_6O_{13}$ whisker	61.6	14.7	46.9
KH550-treated $K_2Ti_6O_{13}$ whisker	50.7	39.9	10.8
OTS-treated $K_2Ti_6O_{13}$ whisker	29.0	28.1	0.9
PTFE	20.3	19.6	0.7

Surface energy of the surface treated $K_2Ti_6O_{13}$ whisker

The surface energy of all samples calculated from Van Oss-Chaudhury-Good function is listed in Table III. It can be seen from Table III that the surface energy of untreated $K_2Ti_6O_{13}$ whisker is the highest among all samples, which is due to lots of hydroxyl groups appeared on its surface.[23] After surface treatment, the surface energy of $K_2Ti_6O_{13}$ whisker decreases dramatically. The conclusion can be drawn out that the treated $K_2Ti_6O_{13}$ whisker is coated with organic modifier.

Table III also shows that the surface energy of OTS-treated $K_2Ti_6O_{13}$ whisker is only 29.0 mJ/m^2, which is the lowest among all $K_2Ti_6O_{13}$ whiskers. And the surface energy of OTS-treated $K_2Ti_6O_{13}$ whisker is near the value of pure PTFE. Based on the similar substance principle, it can be inferred

TABLE II
Water Contact Angle of $K_2Ti_6O_{13}$ Whisker and Polymer

Item	Unmodified $K_2Ti_6O_{13}$ whisker	KH-550 modified $K_2Ti_6O_{13}$ whisker	FSK modified $K_2Ti_6O_{13}$ whisker	OTS modified $K_2Ti_6O_{13}$ whisker	Pure PTFE
Water contact angle	5.2 ± 2.0°	47.9 ± 2.0°	39.8 ± 2.0°	103.5 ± 2.0°	113.6 ± 2.0°

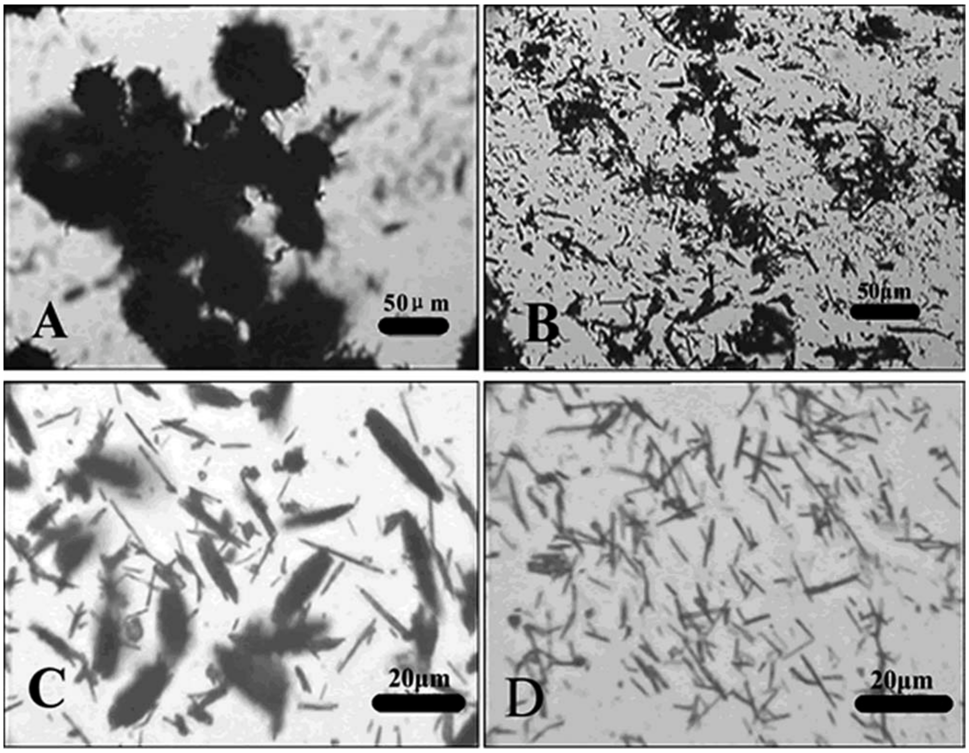

Figure 4 Optical microscope photos of surface-treated $K_2Ti_6O_{13}$ whisker: (A) untreated; (B) FSK; (C) KH550; (D) OTS.

that the interface between $K_2Ti_6O_{13}$ whisker and PTFE can be improved after OTS treatment.

Optical microscope analysis of the morphology of the surface treated $K_2Ti_6O_{13}$ whisker

To explain the effect of surface modification on the dispersion behavior of $K_2Ti_6O_{13}$ whisker, the micrographs of untreated and surface treated $K_2Ti_6O_{13}$ whisker were obtained by an optical microscope. Figure 4 shows a typical optical image of untreated, FSK, KH-550 and OTS-treated $K_2Ti_6O_{13}$ whisker filled PTFE composites. It is clear that there are a lot of agglomerated clusters of $K_2Ti_6O_{13}$ whisker appeared before surface modification [Fig. 4(A)]. The dispersion behavior for FSK or KH-550 treated $K_2Ti_6O_{13}$ whisker [Fig. 4(B,C)] is much better though several small agglomerations are still observed. Moreover, the $K_2Ti_6O_{13}$ whisker is well dispersed after OTS treatment [Fig. 4(D)].

Particles with small size are well recognized to form agglomerated clusters due to the Van Der Waals bonding,[24] which can be attributed to the high surface energy of particles. Thus the agglomeration phenomena of $K_2Ti_6O_{13}$ whisker is strongly improved after surface treatment (Fig. 4). It should

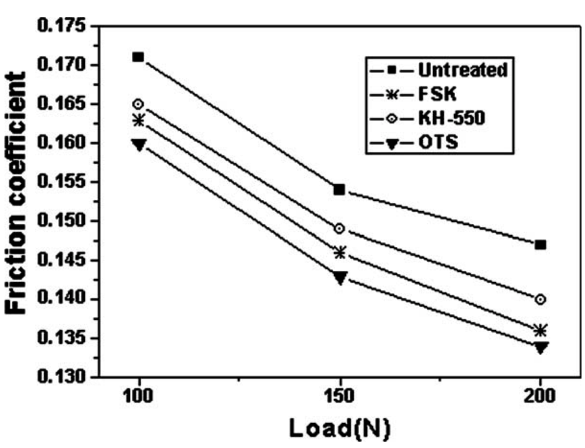

Figure 5 The friction coefficient of PTFE composites filled with surface-treated $K_2Ti_6O_{13}$ whisker.

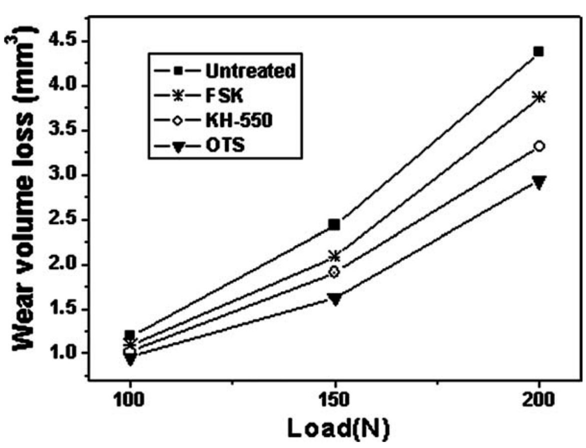

Figure 6 The wear volume loss of PTFE composites filled with surface-treated $K_2Ti_6O_{13}$ whisker.

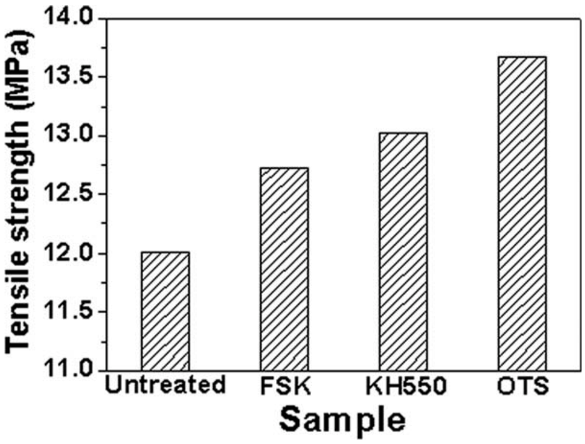

Figure 7 The effect of surface modification on the tensile strength of $K_2Ti_6O_{13}$ whisker filled PTFE composites.

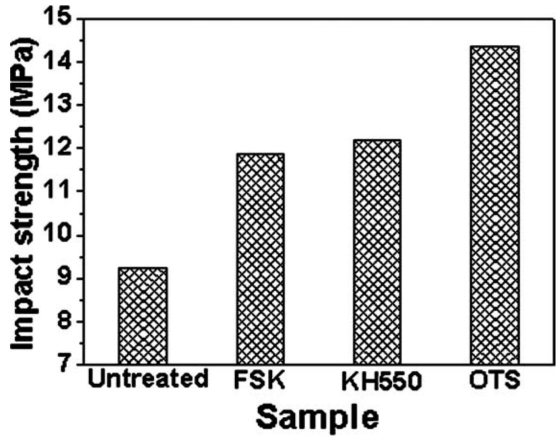

Figure 8 The effect of surface modification on the impact strength of $K_2Ti_6O_{13}$ whisker filled PTFE composites.

be useful to improve the properties of $K_2Ti_6O_{13}$ whisker filled PTFE composites after the surface treatment of $K_2Ti_6O_{13}$ whisker.

Friction and wear behavior of $K_2Ti_6O_{13}$ whisker filled PTFE composites

The friction coefficient and the wear volume loss of PTFE composites filled with untreated and surface treated $K_2Ti_6O_{13}$ whisker are shown in Figures 5 and 6. It can be seen from Figure 5 that the friction coefficient of $K_2Ti_6O_{13}$ whisker filled PTFE composites decreases when filled with the modified $K_2Ti_6O_{13}$ whisker as compared with untreated whisker. The friction coefficient of $K_2Ti_6O_{13}$ whisker filled PTFE composites decreases with the increase of normal load. And OTS-treated $K_2Ti_6O_{13}$ whisker filled PTFE composite shows the lowest friction coefficient under all loads, which is decreased 5 to 8% than that of untreated $K_2Ti_6O_{13}$ whisker filled PTFE composite.

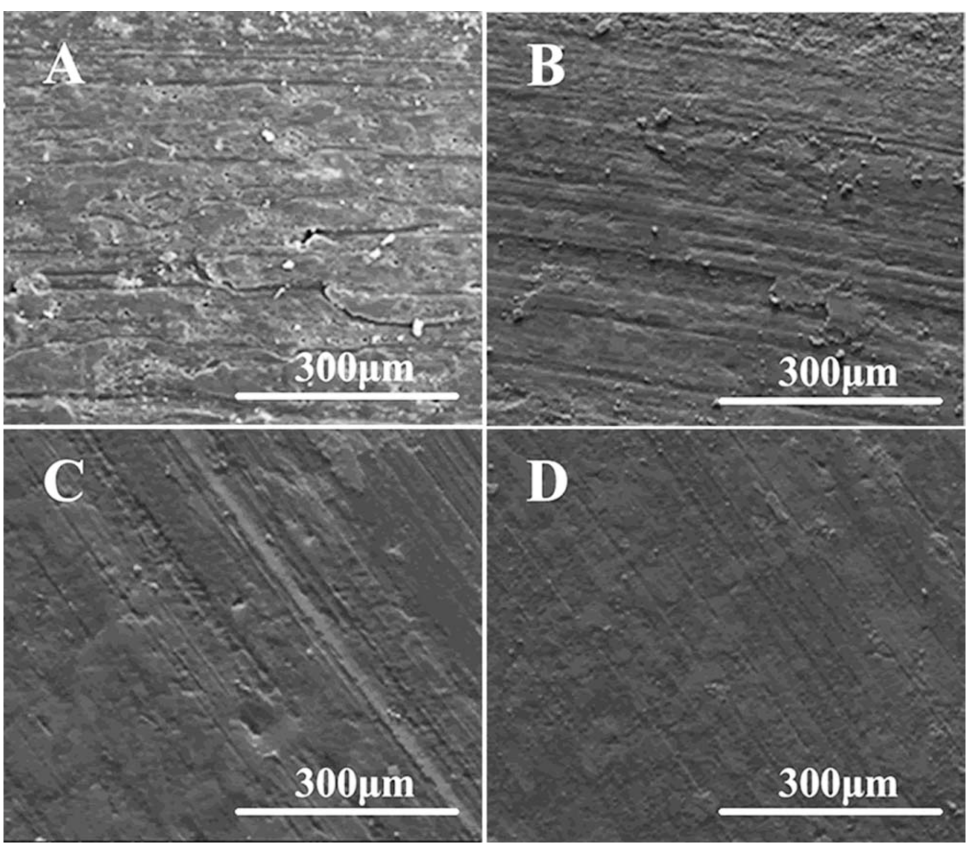

Figure 9 The SEM photos of the worn surfaces of $K_2Ti_6O_{13}$ whisker filled PTFE. A, Untreated; B, FSK; C, KH-550; D, OTS.

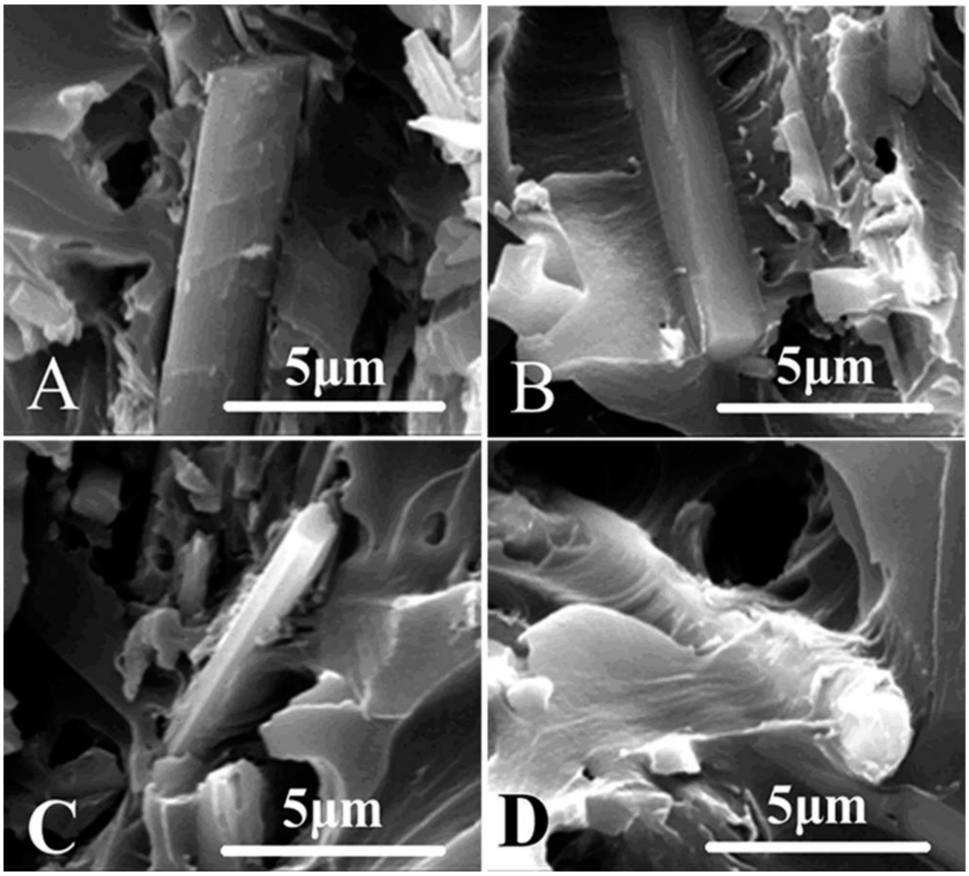

Figure 10 SEM image of impact fracture surfaces of $K_2Ti_6O_{13}$ whisker filled PTFE composites: A, untreated; B, FSK; C, KH-550; D, OTS.

As we can see from Figure 6, the wear volume loss of $K_2Ti_6O_{13}$ whisker filled PTFE composites increases with the increase of normal load. Also the wear volume loss of $K_2Ti_6O_{13}$ whisker filled PTFE composites is obviously changed after the surface modification. The PTFE composite filled with OTS-treated $K_2Ti_6O_{13}$ whisker shows the lowest wear volume loss under all testing loads, which is about 19 to 33% lower than that of the PTFE filled with untreated $K_2Ti_6O_{13}$ whisker.

As a result, OTS-treated $K_2Ti_6O_{13}$ whisker filled PTFE composite is the best from both friction and wear point of view. This indicates that the OTS treatment is more effective in improving the wear resistance ability of $K_2Ti_6O_{13}$ whisker filled PTFE composites than the influence of fluorosurfactant and silane coupling agent treatment. Based on the surface energy results, it can be concluded that reducing the difference between the surface energy of the filler and that of the matrix is good for the improvement of the friction and wear properties of PTFE composites.

Tensile properties and impact properties of $K_2Ti_6O_{13}$ whisker filled PTFE composites

The tensile properties and impact properties of $K_2Ti_6O_{13}$ whisker filled PTFE composites are shown in Figures 7 and 8. As shown in these two figures, the tensile strength and impact strength of PTFE composites were increased after the surface modification of $K_2Ti_6O_{13}$ whisker. It can also be seen that, the PTFE composite filled OTS-treated $K_2Ti_6O_{13}$ whisker shows the highest tensile strength and impact strength, which is about 15 and 55% higher than that of untreated $K_2Ti_6O_{13}$ whisker filled PTFE.

As we know, interface properties play an important role in the performance of composites. To achieve good interface properties, the surface energy difference between the filler and the matrix should be reduced to a small value, which can make the melt polymer matrix spread out on the filler's surface well. Thus based on the mechanical test results it can be concluded that the interface property between $K_2Ti_6O_{13}$ whisker and PTFE is improved after the surface treatment of $K_2Ti_6O_{13}$ whisker, which is in agreement with the results of friction and wear tests.

SEM analysis the worn and impact-fractured surfaces of $K_2Ti_6O_{13}$ whisker PTFE composites

To understand the effect of the surface modification of $K_2Ti_6O_{13}$ whisker on the friction and wear behavior of $K_2Ti_6O_{13}$ whisker filled PTFE composites, the worn surfaces of untreated and surface treated $K_2Ti_6O_{13}$ whisker filled PTFE composites were studied by SEM (Fig. 9). Some deep furrows, which were caused by the abrasive friction behavior between the peeled $K_2Ti_6O_{13}$ whisker and PTFE composite, appear on the worn surface of untreated $K_2Ti_6O_{13}$ whisker filled PTFE [Fig. 9 (A)]. This indicates that abrasive wear is the dominant wear mechanism of untreated $K_2Ti_6O_{13}$ whisker filled PTFE.

In contrast, less and lower furrows appear on the worn surface of FSK or KH-550 treated $K_2Ti_6O_{13}$ whisker filled PTFE composite [Fig. 9(B,C)]. Moreover, there is only several light nicks on the surface of OTS-treated $K_2Ti_6O_{13}$ whisker filled PTFE composite [Fig. 9(D)]. Namely, the abrasive wear of PTFE is dramatically reduced after the surface modification of $K_2Ti_6O_{13}$ whisker, which means that OTS treatment can improve the interaction of $K_2Ti_6O_{13}$ whisker and PTFE greatly. It may be attributed to the smaller difference of surface energy between OTS treated $K_2Ti_6O_{13}$ whisker and PTFE. The above investigation is also consistent with the wear volume loss data of PTFE composites.

To study the interface property of $K_2Ti_6O_{13}$ whisker filled PTFE composites, the impact fracture surfaces of PTFE composites were also investigated by SEM (Fig. 10). It can be seen from Figure 10(A) that there are some obvious gaps between $K_2Ti_6O_{13}$ whisker and PTFE. The interfacial adhesion behavior between $K_2Ti_6O_{13}$ whisker and PTFE is increased after the surface treatment of $K_2Ti_6O_{13}$ whisker despite some pooling out behavior is still can be found [Fig. 10(B–D)]. Furthermore, among the three treatments, OTS modification is the most effective method in improving the adhesion behavior between $K_2Ti_6O_{13}$ whisker and PTFE. The strong adhesion between $K_2Ti_6O_{13}$ whisker and PTFE matrix prevents the failure of PTFE, which improves the mechanical properties of PTFE composites.

CONCLUSIONS

1. The water contact angle of OTS treated $K_2Ti_6O_{13}$ whisker (103.5°) is the biggest among all samples, which is even bigger than that of pure PTFE (113.6°).
2. The surface energy of $K_2Ti_6O_{13}$ whisker decreases dramatically after the surface treatment. And the surface energy of OTS-treated $K_2Ti_6O_{13}$ whisker is only 29.0 mJ/m^2, which is the lowest among all $K_2Ti_6O_{13}$ whiskers.
3. Among all samples, the antiwear property, tensile strength and impact strength of OTS-treated $K_2Ti_6O_{13}$ whisker filled PTFE is the best, which is about 19 to 33%, 15 and 55% higher than that of untreated $K_2Ti_6O_{13}$ whisker filled PTFE.
4. Reducing the surface energy difference between the filler and the matrix is good for the improvement of the tribological and mechanical properties of PTFE composites.

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