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Frictional Wear of Potassium Titanate Whisker Filled Carbon Fabric/Epoxy Composites

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A carbon Fabric/epoxy composite material can be prepared with carbon Fabric as the reinforcement phase and epoxy resin as the binder phase. Use it as the substrate, add six potassium titanate whisker (SPTW) therein, a nano-modified composite will be prepared to investigate how its friction and wear are subjected to change with different loads and what effect the fillers of different doses play on the tribological properties of the composites. Beyond that, its wear mechanism is also discussed herein. The results reveal that the SPTW can exert a good wear resistance effect; there is an optimal dosage of 2.0% for SPTW. In this process, the wear mode of the composite material turns from brittle peeling to adhesive wear.

1. Introduction

Polymer matrix composite is increasingly applied in the mechanical friction field thanks to its light weight, high strength, abrasion resistance, and high load carrying capacity. The thermosetting polymer epoxy resin (EP) presents an excellent adhesion since the epoxy groups in the structure can interact with active hydrogen groups on the surface of the metal material to generate a chemical bond, often used as a protective coating smeared on the surface of metal parts so as to improve their wear resistance. But unluckily, the pute epoxy resin has a large brittleness because it is limited by its own 3D network cross-linking structure. Its antistripping and wear resistance are also inferior to other materials such as polyether ether ketone, PTFE, nylon, etc. For these reasons, it is difficult for this material to well fit the bill for stricter conditions in practices. For this purpose, people generally compound epoxy resin and other materials in an attempt to acquire a better wear resistance (Kanchanomai et al., 2011; Srinivas and Bhagyashekar, 2014; Brostow et al., 2010; Guermazi et al., 2014).

Carbon Fabric /epoxy (CF/EP) is a new type of composite material developed in recent years. With the CF as the substrate and the epoxy resin as the binder phase, this type of composite can enable high modulus, light weight, wear resistance, good toughness, and self-lubrication, as well as the adhesion of EP which can effectively attach to the surface layer of the material to form a gasket material or anti-wear coating applicable to the harsh friction environment. In this sense, it indeed has an excellent usability and promising prospects (Andrich et al., 2013; Veerapaneni and Daudu, 2015; Guo et al., 2009; Zhang et al., 2010; Pan et al., 2014).

Inorganic whiskers are acicular monocrystal Fabric materials developed in recent years, where atoms in the monocrystal are well arranged to almost overcome various defects of polycrystalline materials. As this material features interface regularity, high draw ratio, high strength, fine structure, and high modulus, etc., it can uniformly disperse in the polymer after modification to serve as a skeleton support. Additionally, it will be able to form a polymer-whisker composite material, thereby making polymer exhibit good mechanical properties (Zhou et al., 2005; Xu et al., 2013). On this basis, with the SPTW as the filler in this experiment, we aim to study what effect of the fillers of different doses on the tribological properties of carbon Fabric /epoxy resin matrix under different friction conditions, in conjunction with analysis on its friction and wear mechanism herein.

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2. Experiment

2.1 Raw materials and major equipment

Epoxy Resin (E-44, Zhenjiang Danbao Resin Co., Ltd.); Low Molecular Weight Polyamide (650, Zhenjiang Danbao Resin Co., Ltd.); Butanone (AR, Xi'an Chemical Reagent Factory); Toluene (AR, Tianjin Da Mau Chemical Reagent Factory); carbon Fabric flat fabric (for parameters, see Table 1, Jiangsu Tianniao Company); potassium hexatitanate whiskers (density (g/cm3): 0.4-0.6, surface area (m2/g): 0.40-1.00, Shanghai Fengzhu New Material Technology Co., Ltd.); Silane Coupling Agent (KH550, Nanjing Daoning Coupling Agent Co., Ltd.); Ultrasonic Cleaner (KQ3200E, Kunshan Ultrasonic Instrument Co., Ltd.); Magnetic Stirrer (ZNCL -S, Zhengzhou Kaipeng Test Instrument Co., Ltd.); wear tester (MM-200, Xuanhua Tester Factory).

Table 1: Parameters of plain weave carbon Fabric fabric

Type	Reinforcement Yarn		Weave	Fiber Count(10mm)		Weight (g/m2)	Width (mm)	Thickness (mm)
	Warp Yarn	Weft Yarn		Warp Ends	Weft Picks			
HY-1K-P	1K	1K	Plain	10.5	10.5	140	100	0.17

2.2 Sample preparation

2.2.1 Preparation of epoxy resin components

The epoxy resin binder phase used in this test contains two components, i.e. A and B. In the component A, the substrate epoxy resin and diluent butanone are made up by a ratio of m_{ep} : v_{bu} =1:2.4; In the component B, the curing agent polyamide and the diluent toluene are also prepared by the ratio of m_{po}:v_{to}=1:2.4.

2.2.2 Surface treatment of carbon Fabric and SPTW

Cut the appropriate size of carbon Fabric, soak it in acetone solution, ultrasonically clean it at room temperature for 2h, and then it is shifted to a constant temperature drying oven at 80 °C and dried out for 24h. The appropriate mass of KH-550 silane coupling agent is weighed at a ratio of 2% of the carbon Fabric /epoxy and prepared into a 90% ethanol solution. The SPTW is then added, after stirring this mixture magnetically for 60 minutes, it is evaporated to dryness at 120C and cooled to room temperature to prepare a modified SPTW.

2.2.3 Preparation of carbon Fabric /epoxy composite

The component A is added with the appropriate mass fraction of the modified SPTW, and the carbon Fabric is repeatedly dipped and smeared with the epoxy resin mixed with component B at a ratio of 1:1 uniformly until the carbon Fabric accounts for 60% ~70% of the mass fraction of the composite material. In the end, the composite material is finally bonded to the surface of the 45# steel block, and cured under a vacuum condition of 0.1MPa at 80°C for 2 h so that a test sample is prepared.

2.3 Test method

2.3.1 Tribological property test

The MM-200 ring-block wear and abrasion tester is used to evaluate the tribological property of the material. The initial pair grinding thickness of the carbon Fabric /epoxy resin composite is 1.5 mm, and the coated steel block is 20 mm× 8 mm×11 mm in size. Friction pair uses quenched 45# steel ring with hardness of 40~50HRC and of size of ø50 mm×10 mm. Prior to the wear and abrasion test, the surface of steel ring is ground in turn with 800# and 1200# water-based sandpaper to a surface roughness of Ra=0.2-0.45μm, and wiped clean with acetone. During the test, the sliding friction is maintained at a linear velocity of 0.54m/s, the test duration is 30min for each group, the applied loads are in turn 150N and 200N, and the relative humidity is 50±5%. All tests are dry friction conducted at room temperature.

The friction coefficient μ of the material during the test can be calculated by reading the friction torque on the tester and using the following formula:

$$\mu=M/(R\times P) \tag{1}$$

Where, M is the friction torque, N * m; R is the radius of pair steel ring, m; P is the applied load, N;

After the test, the wear depth of the carbon Fabric /epoxy resin composite is measured using a digital micrometer traceable to 0.001 mm. Additionally, its wear life can also be calculated by dividing the sliding friction distance by the wear depth to characterize the wear resistance of material itself:

$$W=(V\times t)/\triangle H \quad (2)$$

Where, V is the linear velocity of friction, m / s; t is the friction test time, s; $\triangle H$ is the wear depth, μm.

2.3.2 SEM analysis of SPTW

The microstructures of SPTW and composites are observed by JEOL-2010 Scanning Electron Microscope (SEM). The voltage is kept at 20Kv, and the sample surface is applied with a thin layer of gold powder.

2.3.3 Analysis of composite wear morphology

At the end of the test, the surface of the worn specimen is sprayed with gilding and then placed under a JSM-5610LV SEM for morphology analysis at the acceleration voltage of 20 kV.

3. Results and discussion

3.1 Morphology and physical properties of SPTW

The SEM image of SPTW is shown in Figure 1.

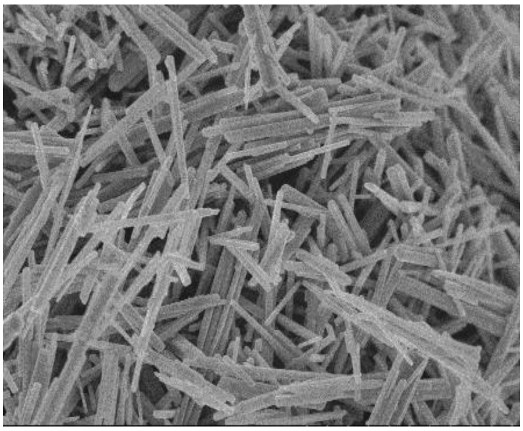


Figure 1: The SEM picture of six potassium titanate whisker

The chemical formula for potassium titanate whisker is generally $K_2O.n(TiO_2)$ (n=1~8) or $K_2Ti_2O_{2n+1}$, whilst n = 2, 4, 6 is often used in the industry, called the Potassium Dititanate Whiskers (PDW), Potassium Tetratitanate Whiskers (PTW) and Potassium Hexatitanate Whiskers (PHW), respectively. Among them, the PTW has a good chemical activity, and the PHW has a tunnel structure, which is resistant to corrosion and abrasion and has a better stability, good mechanical and physical properties. In order to visualize the morphology of the PHW more clearly, the whiskers can be observed with a SEM. An SEM photograph for PHW at 1000 times is shown in Figure 1. It is obvious that the PHW has an acicular crystal structure with a draw ratio of about 1:20 and its aquatic dispersion PH value of 7-9, resistant to acid and alkali, specific surface area of 11 $m^2 \cdot g^{-1}$, infrared transmittance of 8.4% (0.25 mm thick), Mohs hardness of 4, diameter of 0.8-1 μm, actual density of 3.28 -5.53 $g \cdot cm^{-3}$, bulk density of 0.1-0.3 $g \cdot cm^{-3}$, good hydrophilicity, poor compatibility with organic solvents, and thermal expansion coefficient of $6.8\times10^{-6}K^{-1}$.

3.2 Wear properties of SPTW filled carbon Fabric /epoxy resin composites

3.2.1 Analysis

The curve of friction coefficient of carbon Fabric /epoxy resin composites simply filled with SPTW under 150N and 200N test conditions is shown in Figure 2.

As shown in the figure, the friction coefficient of the pure carbon Fabric /epoxy resin composite is stable at between 0.17 ~ 0.22, and goes up slightly with the increase of the loads; under a load of 150 N, the different dosage of SPTW has little effect on the friction coefficient of the composites. The friction coefficient shows a tendency to upward and downward fluctuate as the dosage of filler increases. When the filler dosage is 2%, the friction coefficient of the composite material is the lowest value of 0.1734, compared to the pure carbon Fabric /epoxy resin composite, the friction coefficient decreases by 12.73%; under 200N load conditions, the friction coefficient of the composite exhibits a tendency to decrease and increase as the dosage of SPTW builds up. When the filler reaches 2%, the friction coefficient of the composite takes the lowest value of 0.1848, compared with the pure material, reduced by 14.96%, so that the effect is improved significantly.

In Figure 3(a) and Figure 3(b), the wear lives of carbon Fabric /epoxy resin composites purely filled with SPTW under 150 T and 200 N test conditions, respectively, are compared.

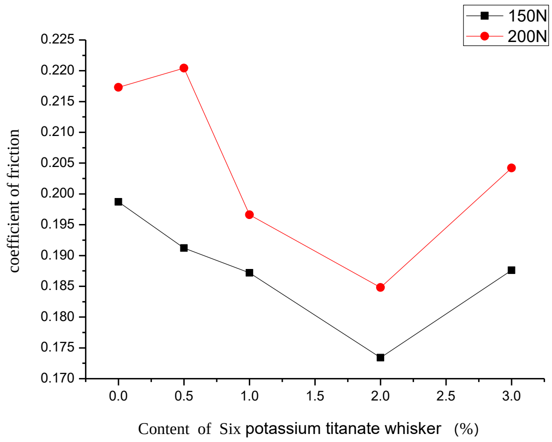
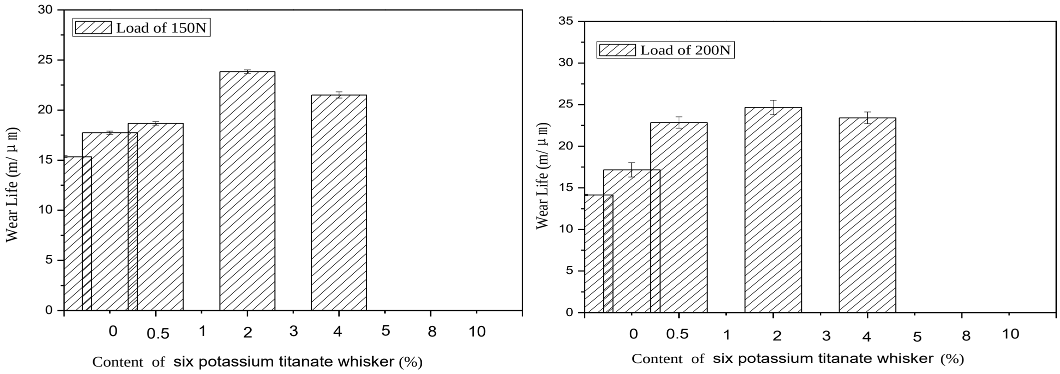


Figure 2: Effects of addition amount of six potassium titanate whisker on the friction coefficient of CF/EP composites under different loads



(a) Load of 150N (b) Load of 200N

Figure 3: Variation of wear life of CF/EP composites with different six potassium titanate whisker contents under different loads

From Figure 3(a), it can be seen that under 150 N load conditions, the wear life of CF/EP composite first increases and then decreases as the dosage of SPTW builds up. When the filler is 2%, the wear life of the modified composite reaches 23.84m/μm, and 55.39% higher than that of the unmodified CF/EP material; when it exceeds 2%, the wear properties of the composites get deteriorated. When 200N load is applied, as shown in Figure 3(b), the wear life of the composite changes significantly different from that under the 150N load condition, and the overall trend of the curve presents more “steep”; when the content of filler SPTW increases from 0% to 3%, the wear life of the composite changes from 14.15 m/μm to 24.67 m/μm, increased by 74.34%; when the load increases from 150N to 200N, the enhanced wear life of pure CF/EP materials shortens due to external shear, whilst the modified CF/EP composites with SPTW extends its wear life a little, which suggests that the SPTW can fully exert a wear resistance reinforcement effect on CF/EP substrates under a higher loading conditions.
The SEM is used to further observe the wear morphology of unmodified and modified CF/EP materials with 2% SPTW at 150N and 200N loads, respectively, as shown in Figure 4.
As shown in Figure 4(a), for the unmodified CF/EP substrate material after a certain time of wear under a load of 150 N, a deep groove-like scratch appears on the mating interface, the bulk blocks of adhesive resin phase are destroyed and peeling off. The only part of the resin substrate available has plastic deformation caused by extrusion, intermittently distributed on the surface of the material in the form of islands, and many cutting-off Fabrics are exposed, showing brittle stripping and adhesive wear morphologies on the whole; After 2%

SPTWs are filled, the shedding of the adhesive resin on the wear surface is actively suppressed, the wear scar is relatively shallow, and no more Fabric are seen to expose, as shown in Figure 4 (b, c); when the load builds up to 200N, the unmodified CF/EP matrix material is subjected to a more severe shear action, more Fabrics in the deep surface layer are pulled out and cut off, and the interface is unsmooth, as shown in Fig. 4(d), more severe fatigue wear form appears; as shown in Figure 4(d) and 5(d), the CF/EP composite material modified by 2% SPTW under 200N load condition is worn. It can be seen that the material structure is well maintained, and some cluster-like abrasive dust particles are scattered in the surface layer, but do not cause severe plowing scratches; the overall surface is relatively smooth, exhibiting a sheet-like adhesive transfer morphology along the sliding direction.

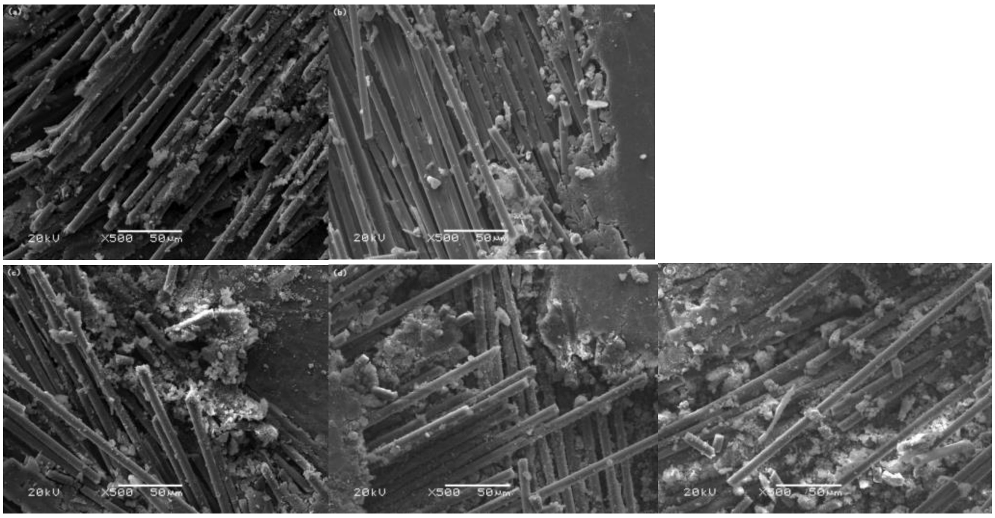


Figure 4: (a-e) SEM micrographs of the worn surfaces of composites (Load of 150N)

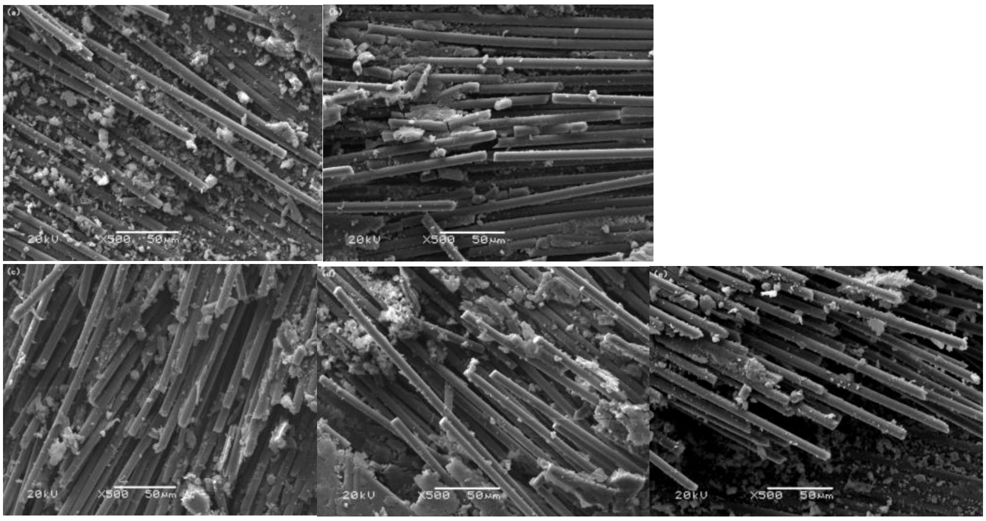


Figure 5: (a-e) SEM micrographs of the worn surfaces of composites (Load of 200N)

Based on the above characteristics, the epoxy resin on the surface layer of unmodified CF/EP material has a large brittleness, and is more prone to cracking and shedding off under the action of the shear force of the mating part. A part of Fabrics reinforced at the depth of the surface layer are also pulled out and broken off because the abrasion resistance of carbon Fabric is far better than that of epoxy resin bonding phase. For this reason, it can be inferred that the structural component that plays a major support role in the wear process is still a carbon Fabric layer. But badly, although carbon Fabric can have wear resistance thanks to high-strength and high-modulus properties, as well as self-lubrication capacity, it also belongs to a material with high brittleness. In the harsher friction environment, once the carbon Fabric gets thin by wear, it is easy to generate

debris residues with high hardness, which in turn causes serious abrasive plowing score on the epoxy substrate until it fractures. At this time, it means that the material has exhausted its wear resistance.
After adding a certain amount of SPTW, the wear properties of the CF/EP material will be improved due to its dispersion strengthen effect. When the dosage of SPTW is 2%, CF/EP substrate has a better wear resistance and reduction effects. But evaluating from the whole process, the wear coefficient tends to change ups and downs with the increase of the dosage of the filler. There is still a part of the brittle shedding pits on the worn surface. It is supposed that this may have a direct bearing on the aggregate distribution and loss of SPTW fillers in CF/EP substrates.

4. Conclusions

(1) Carbon Fabric /epoxy composite material added with a proper dose of SPTW can play a good wear resistance effect. For the SPTW additive, there is an optimal dose of 20%. At a higher load, the composite has a lower friction coefficient and higher wear life.
(2) Unmodified carbon Fabric /epoxy composite mainly exhibits such wear morphologies as fatigue wear and brittle exfoliation. With the increase in the dose of SPTW, the wear mode of the materials gradually shifts to adhesive wear.

Acknowledgments

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