J Mater Sci (2015) 50:1065–1070
DOI 10.1007/s10853-014-8663-8

WS_2-filled hybrid PTFE/Nomex fabric composites with improved antiwear property

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Received: 12 August 2014 / Accepted: 8 October 2014 / Published online: 15 October 2014

Abstract Exploring effective lubricant fillers to improve the tribological performance of the fabric composites would have practical applications. Herein, we developed nano- and micro-dimensional WS_2 as fillers to improve the tribological property of the hybrid PTFE/Nomex fabric/phenolic composite. Sliding wear tests showed that the WS_2-filled fabric composites displayed improved antiwear behavior under all the test conditions, compared to the unfilled one. The optimum content of WS_2 to fill the fabric composites was 2 wt% for nano-dimensional WS_2 and 4 wt% for micro-dimensional WS_2. We also investigated the unfilled, nano-dimensional WS_2-filled, and micro-dimensional WS_2-filled fabric composites under varied test conditions, and the corresponding wear mechanisms were discussed based on the characterizations.

Introduction

Fabric-reinforced polymer composites have recently generated immense interests due to their excellent specific strength, corrosion resistance, self-lubricating properties, wear resistance, and light weight [1–3]. Among the fabric composites investigated, hybrid PTFE/Nomex fabric composite was one of the most widely used ones because of its excellent performances and can be applied as liner and structural materials [4–6]. To take full advantage of hybrid PTFE/Nomex fabric composite, the face of the hybrid fabric rich in PTFE fiber was subjected to wear due to its low-friction property, while the other face rich in Nomex fiber adhered onto the substrate [7]. However, the invalidation of hybrid PTFE/Nomex fabric composite will always be accelerated due to the limited antiwear property of PTFE fiber [8, 9]. Therefore, it is urgently demanded to improve the antiwear property of the hybrid PTFE/Nomex fabric composites.

To improve the tribological properties of the fabric composites, surface modification of fabric and filler reinforcing have proven to be the effective ways. Particularly, the incorporation of lubricants or nanoparticles into fabric composites is easy-handling and displays tremendous promise in achieving longevity and desired tribological properties [10–12]. WS_2, which displays lamellar structure, high oxidation temperature, and low friction coefficient and which is easy to be sheared to form lubricious transfer films between the friction pair interface, is expected to be an ideal solid lubricant to improve the tribological property of fabric composites [13–15]. Although numerous fillers have been developed to improve the tribological property of fabric composites, research focused on developing WS_2 as the lubricant filler is relatively rare till now.

In this study, to investigate the influence of WS_2 filling on the friction and wear behaviors of fabric composite, we developed WS_2 as the filler for PTFE/Nomex fabric composite. The potential effects of dimension and filling content of WS_2 on the tribological property of the fabric composite were studied. Furthermore, friction and wear behaviors of unfilled and optimized content of WS_2-filled fabric composites were analyzed systematically. This work

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is hoped to extend the duration and application of the fabric composites.

Experimental

Materials

The satin-weave hybrid PTFE/Nomex fabric (volume fraction of PTFE to Nomex: 1:3) was woven out of PTFE fibers (fineness: 400 Denier) and Nomex fibers (fineness: 200 Denier) purchased from DuPont Plant. The adhesive resin (204 phenolic resin: resol) was provided by Shanghai Xing-guang Chemical Plant, China. Nano-dimensional WS_2 (50–120 nm in diameter) and micro-dimensional WS_2 (0.85–1.15 μm in diameter) were provided by Changsha Huajing Material Technological Co. Ltd, China. The rest of the chemicals were all of analytical grade and used as received.

Preparation of hybrid fabric/phenolic composites

The hybrid PTFE/Nomex fabric was cleaned with petroleum ether and ethanol sequentially in Soxhlet extractor and then dried in an oven at 50 °C. Subsequently, the pristine hybrid fabric was immersed in the adhesive solution with the content of nano-dimensional WS_2 between 0 and 6 wt%. After several cycles of immersion and coating, the mass fraction of the hybrid PTFE/Nomex fabric in the fabric/resin composite reached to about 70 ± 5 %. Finally, the prepregs were cut into pieces and adhered onto the AISI-1045 steel (size of Φ 45 mm × 8 mm, surface roughness of 0.45 μm) using 204 phenolic resin and then cured at 180 °C for 2 h. Micro-sized WS_2-filled fabric composite with the filler content between 0 and 8 wt% was prepared according to the same procedure.

Friction and wear test

The Xuanwu-III pin-on-disk tribometer (see Fig. 1) was applied to investigate the tribological properties of hybrid PTFE/Nomex fabric/phenolic composite. In this pin-on-disk tester, a stationary steel pin (2 mm in diameter) was employed to slide against the fabric composite specimen. Prior to each test, the pin was polished with 350, 700, and 900 grade water-proof abrasive papers sequentially and then cleaned with acetone. Sliding wear tests were conducted on this pin-on-disk tester for 2 h under ambient condition. At the end of each test, the corresponding wear volume loss (V) of the composite was obtained by measuring the depth of the wear scar on a micrometer (resolution: 0.001 mm). The wear performance was expressed by wear rate (ω, m^3 $(Nm)^{-1}$) as follows: $\omega = V*(PL)^{-1}$,

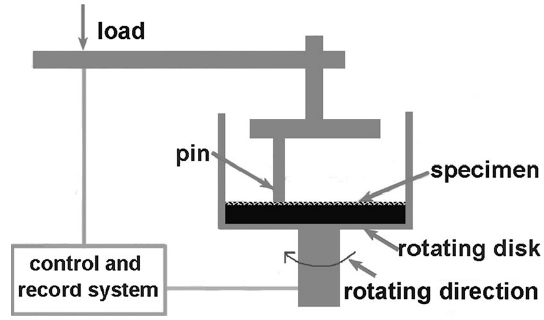

Fig. 1 Schematic diagram of the pin-on-disk wear tester

where V is the wear volume loss in m^3, P is the load in Newton, and L is the sliding distance in meter. Each experiment was carried out three times, and the average value was used.

Morphology and microstructure of WS_2 was investigated by FEI Tecnai F30 transmission electron microscopy (TEM). The EDXA images and SEM images were acquired on a JSM-5600LV scanning electron microscope (SEM) equipped with an energy-dispersive X-ray analyzer (EDXA).

Results and discussion

Texture analysis of WS_2

Figure 2 showed the texture of the nano- and micro-dimensional WS_2. It can be seen that the WS_2 exhibited the assembled flowerlike clusters, which were composed of a number of distorted nano-dimensional WS_2 or micro-dimensional WS_2 sheets (see Fig. 2a, b). Importantly, TEM analysis demonstrated that both the nano- and micro-dimensional WS_2 possessed lamellar structure, similar to other lubricants, and thus it was beneficial to improve the tribological property of the fabric composites (see Fig. 2c, d).

The effect of WS_2 content of the tribological property of the fabric composites

Figure 3 showed the effect of WS_2 content on the tribological properties of hybrid PTFE/Nomex fabric composites. It can be seen that the friction coefficient of nano-dimensional WS_2-filled fabric composites varied slightly with the content of WS_2 increasing, as shown in Fig. 3a. Meanwhile, it was clearly illustrated that the wear rate of nano-dimensional WS_2-filled fabric composite was firstly decreasing and then increasing with the content of WS_2 increasing (see Fig. 3b). Logically, the optimum content was 2 wt% for improving the tribological property of the

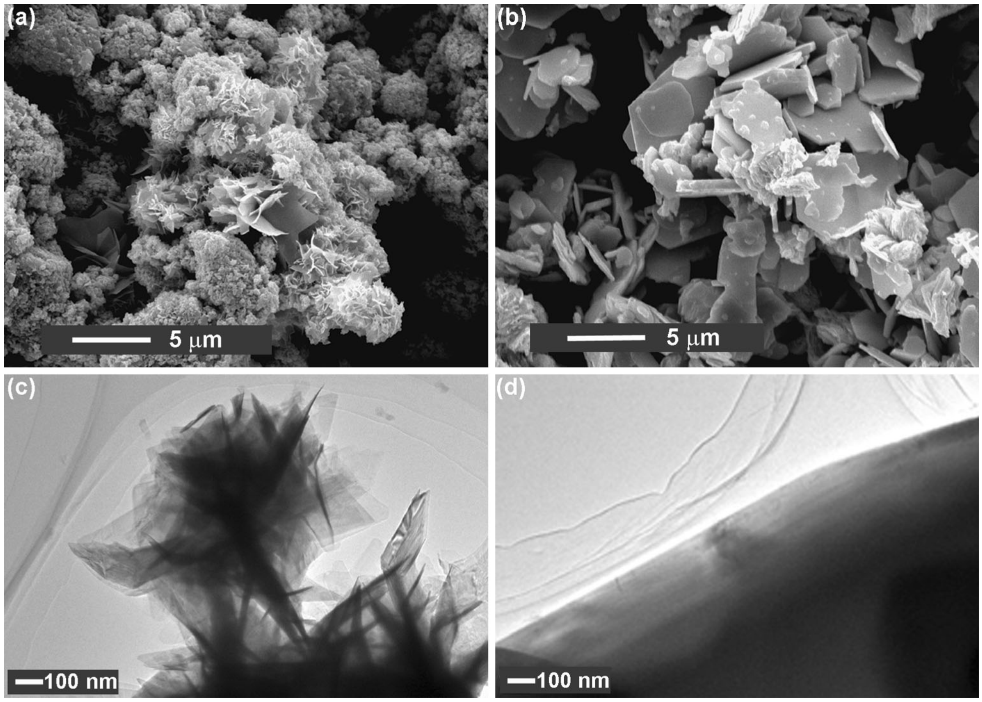

Fig. 2 **a** and **c** are SEM and TEM images of nano-dimensional WS_2, respectively; **b** and **d** are SEM and TEM images of micro-dimensional WS_2, respectively

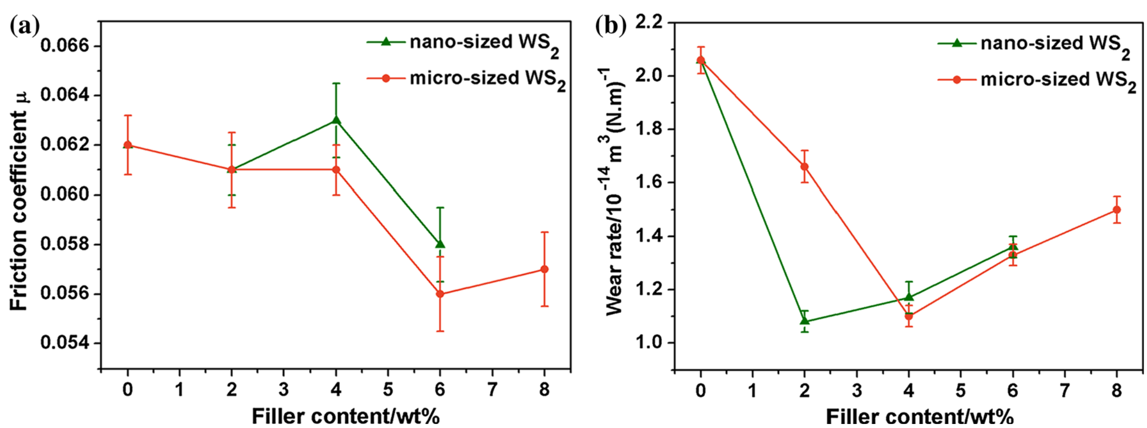

Fig. 3 Variation of friction coefficient (**a**) and wear rate (**b**) of hybrid PTFE/Nomex fabric with the content of nano-dimensional WS_2 and micro-dimensional WS_2. The applied load and sliding speed in the tests were 100 MPa and 0.26 m/s, respectively

fabric composite, when nano-dimensional WS_2 was employed as the lubricant filler. Moreover, we also investigated the effect of micro-dimensional WS_2 on the tribological property of the fabric composites, and the content to obtain optimum tribological property was 4 wt%.

In the following text, the unfilled fabric composite, 2 wt% nano-sized WS_2-filled fabric composite, and 4 wt% micro-sized WS_2-filled fabric composite were designated as composite A, composite B, and composite C, respectively.

Figure 4 presented the variation of friction coefficients of composite A, composite B, and composite C with sliding time. It can be seen that the duration of running-in stage of composite B and composite C decreased significantly, compared to that of composite A, owing to the quicker formed transfer film [16]. This result indicated that the incorporation of WS_2 into phenolic resin accelerated the formation of transfer film and was beneficial to improve the antiwear property of the fabric composite.

Tribological properties comparison

We next investigated the tribological properties of composite A, composite B, and composite C under varied sliding wear conditions. It can be seen that the antiwear

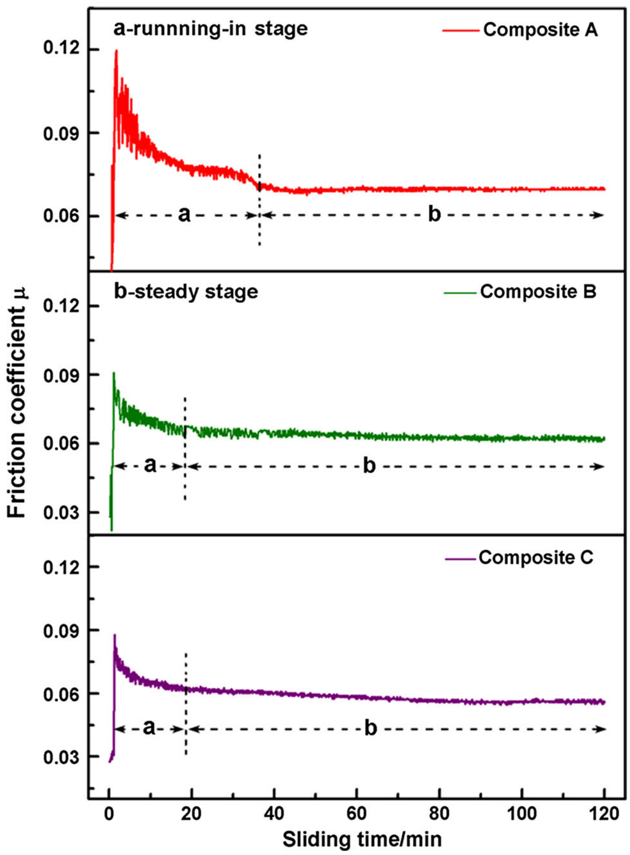

Fig. 4 Friction coefficients of composite A, composite B, and composite C as a function of sliding time. The applied load and sliding speed in the tests were 100 MPa and 0.26 m/s, respectively

property of the fabric composites was improved significantly, when incorporated with WS_2. As illustrated in Fig. 5a, the wear rates of composite B and composite C were much lower than that of composite A under all the investigated sliding wear conditions. The result indicated that WS_2 filling was efficient in improving the antiwear property of the fabric composite, and this improved antiwear property would extend the lifetime of the fabric composite.

We also found that the filling of WS_2 influenced the friction coefficient of hybrid PTFE/Nomex fabric composite slightly, evidenced by the close values of friction coefficient, as shown in Fig. 5b. For PTFE/Nomex fabric/phenolic composite, when the wear depth was low, it was the phenolic matrix that mainly exposed on the worn surface, allowing the fabric composite to display a relatively higher friction coefficient. With the wear depth increasing, more fibers exposed on the worn surface and the friction coefficient became lower. When WS_2 was incorporated into the fabric composites, the wear depth of the composite became lower, which indicated that more resin matrix and less fibers exposed on the worn surface during the sliding wear process. Accordingly, the friction coefficient of the fabric composite varied slightly after being filled with WS_2.

Surface morphology analysis

Since lubricant filling endowed positive effect on improving the antiwear property of the fabric composite, the worn surfaces of the composites were analyzed to understand the wear mechanisms of the three fabric composites. It was found that, for fabric composite without lubricant, the worn surface was characterized by a large amount of cut-down fibers and scarcely any continuous resin matrix (see Fig. 6a, d). It was deduced that during the sliding wear process, the resin matrix detached from the fabric and was severely shelled off. Thereafter, bundles of fiber exposed on the worn surface and were destroyed under the strong shearing force during the sliding wear test. When 2 wt% nano-dimensional WS_2 was incorporated into the resin matrix, the fabric composite exhibited lower wear rate and moderately destroyed worn surface. As shown in Fig. 6b and e, on the worn surface of composite B, most resin

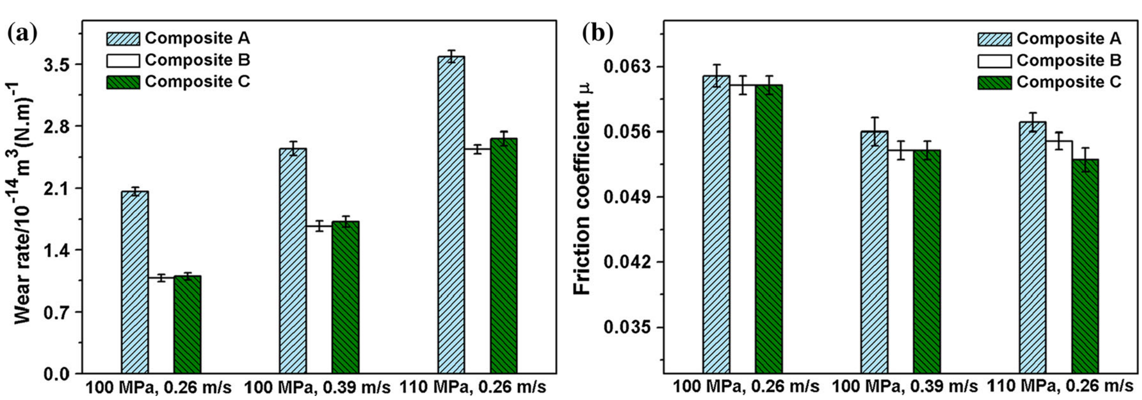

Fig. 5 Friction coefficients (**a**) and wear rates (**b**) of composite A, composite B, and composite C under different sliding conditions

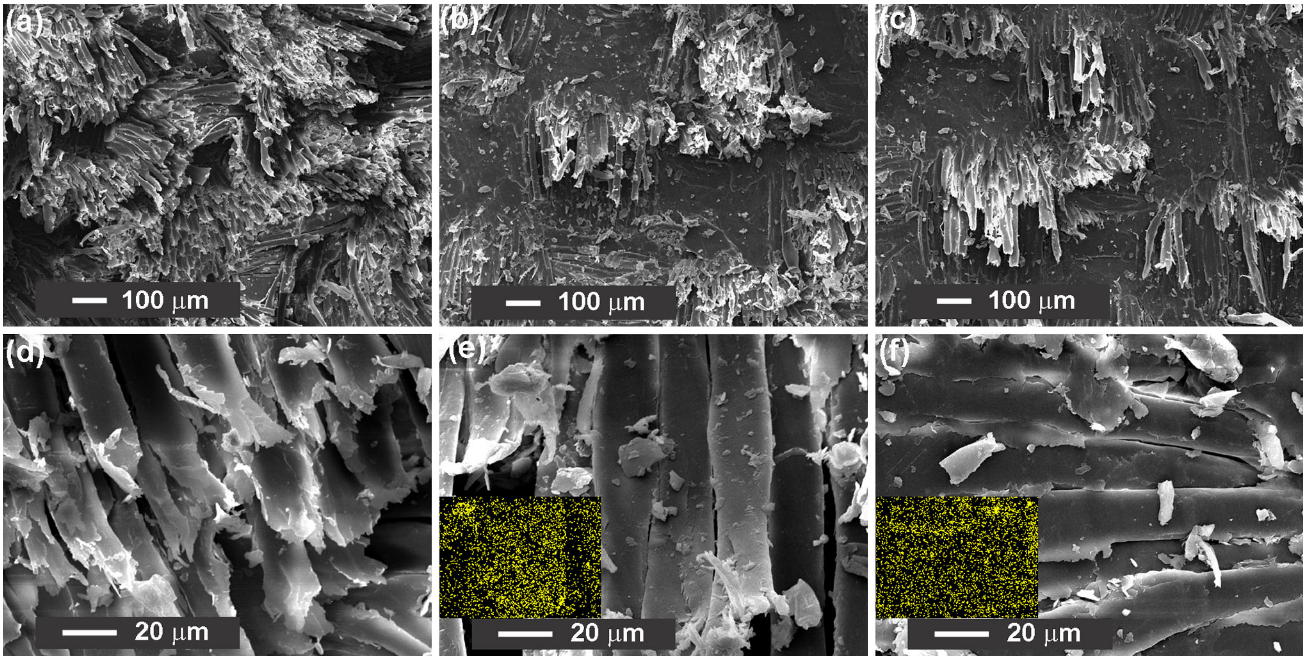

Fig. 6 SEM images of the worn surfaces for **a** composite A, **b** composite B, and **c** composite C; **d**, **e**, and **f** are magnified images of (**a**), (**b**), and (**c**), respectively. The *insets* are the EDXA images of W. The applied load and sliding speed in the tests were 100 MPa and 0.26 m/s, respectively

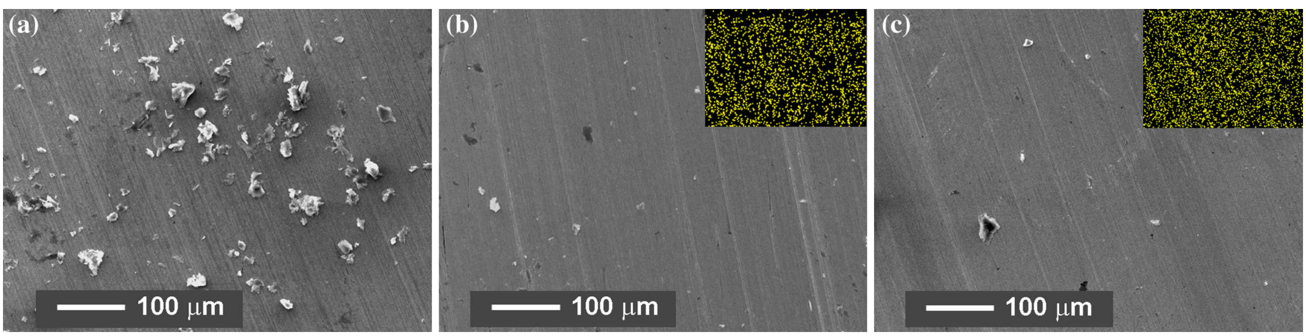

Fig. 7 SEM images of the worn surfaces of the counterpart pins sliding against composite A (**a**), composite B (**b**), and composite C (**c**). The *insets* are the EDXA images of W. The applied load and sliding speed in the tests were 100 MPa and 0.26 m/s, respectively

matrix bonded well with the fabric, and much less exposed and damaged fibers were detected. It can be logically deduced that the lubricating effect of WS_2 contributed to the improved antiwear property of the resin matrix markedly and thus that of the fabric composite [17, 18]. Similarly, the worn surface of composite C was characterized by mild abrasion (see Fig. 6c, e).

In addition, the surface morphology of the counterpart pins sliding against the fabric composites was presented in Fig. 7. For the counterpart pin sliding against the unfilled fabric composite, masses of wear debris and parallel groves were detected on it, indicating severely wear occurred during the sliding wear test. Comparatively, trivial scratches and wear debris were detected on the worn surfaces of the counterpart pins slid against the composite B and composite C. The densely distributed W elements on the counterpart pins slid against composite B and composite C approved the continuous and compact transfer films formed on the pin surfaces [19–21]. The easy-formed films rich in WS_2 decreased the friction between the tribo-pair and protected the pin from serious scratching [19–21]. Whereas, on the worn surface of the counterpart pin slid against composite A, the transfer film formed was discontinuous, and thus composite A displayed a higher wear rate.

Conclusion

Nano- and micro-dimensional WS_2 were developed as fillers to improve the tribological property of the hybrid PTFE/Nomex fabric/phenolic composite. The result of sliding wear tests indicated that the filling with WS_2 affected the friction coefficient of the fabric composites slightly, but improved the antiwear property of the fabric composites significantly. The optimum content of nano- and micro-dimensional WS_2 to fill the fabric composite was 2 and 4 wt%, respectively. Moreover, transfer films formed continuously and compactly on the counterpart pin surface slid against the WS_2-filled fabric composites, compared to the one slid against the unfilled fabric composite.

Acknowledgements The authors acknowledge the financial support of the National Science Foundation of China Grant No. 51375472 and 51305429.

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