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Friction and Wear Properties of Dumbbell-Shaped Jute Fiber-Reinforced Friction Materials

Yunhai Ma,[1,2] Yucheng Liu,[1,2] Shengsheng Ma,[1,2] Hubiao Wang,[1,2] Zhihui Gao,[1,2] Junjie Sun,[1,2] Jin Tong,[1,2] Li Guo[1,2]

[1]Key Laboratory of Bionic Engineering, Jilin University, Changchun 130022, China

[2]College of Biological and Agricultural Engineering, Jilin University, Changchun 130022, China

Correspondence to: L. Guo (E-mail: liguo2012@jlu.edu.cn)

ABSTRACT: The surfaces of jute fibers (*Corchorus capsularis* L.) were processed to have different dumbbell-shaped spacing (5 mm, 10 mm, 15 mm, and 20 mm), and the physical properties of the modified surfaces of the jute fibers were evaluated in this study. The dumbbell-shaped jute fiber (DJF)-reinforced friction materials were prepared through compression mold. The friction and wear performance of the DJF were tested using a friction material tester at constant speed. The results showed that the dumbbell-shaped spacing has less influence on the friction coefficients of friction materials. The friction coefficients of DJF have bigger fluctuation compared with that of straight fiber during the temperature-increasing procedure. The wear rate of DJF with dumbbell-shaped spacing of 15 mm was the lowest, except for that when the temperatures were about 200–250°C. Morphologies of wear surfaces of DJF were observed using scanning electron microscopy and the friction characteristics were analyzed. The results showed that reinforced with DJFs in the friction materials can reduce the specific wear rate and the variation in friction coefficient compared with that of straight jute fibers. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40748.

KEYWORDS: composites; fibers; friction; surfaces and interfaces; wear and lubrication

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INTRODUCTION

Friction materials, which are the key part of brakes, clutches and friction gearings of terrain machines, have been formulated for about 100 years.[1] They directly relate to the reliability and stability of operation system.[2] In addition, the performance of the friction materials is required higher and higher with the development of terrain machines industry and the improvement in environmental awareness.[3] Therefore, the friction materials ought to possess stable friction coefficient and low wear rate over wide ranges of operating speed, load, temperature, and should benefit to environmental protection.[4,5] The fiber-reinforced friction materials are one of the most common products and possess unique self-lubrication capabilities.[6,7] They are multicomponents composites composed of fibers, abrasives materials, lubricants, space fillers, property modifiers, and polymer binders.[8–10] The reinforced fibers play a critical role in determining the mechanical strength, thermal resistance, and friction and wear properties of the friction materials.[11–13]

The ecofriendly fibers have become very important for the friction materials industry since asbestos fibers were found to be harmful to the environment and human health.[14,15] To improve the performance of the friction materials and protect environment, many studies have focused on the substitutes of asbestos fiber, such as jute fibers,[16,17] sisal and flax fibers,[18–21] sugarcane fibers,[22,23] bamboo fibers,[24] and banana fibers.[25–27] Among these fibers, jute fiber has excellent properties with high strength, elastic modulus, biodegradability, nontoxic, low density, low cost and can decrease the wear rate of the surface of coupled parts. With these advantages of physical and mechanical properties, jute fiber becomes an ideal substitution of asbestos and metal fibers in various kinds of friction materials. Goriparthi et al.[28] studied the effect of fiber surface treatments on mechanical and abrasive wear performance of polylactide/jute composites. The results showed that the treated composites with 3-amino propyl trimethoxy silane and the trimethoxy methyl silane had higher thermal stability compared with that of untreated composites; and jute fiber composite treated by trimethoxy methyl silane, which had better fiber substrate adhesion, exhibited maximum abrasive wear resistance. Ma et al.[29] investigated the effect of jute fibers contents on the friction and wear properties of the friction materials. They indicated that the friction coefficients of friction materials

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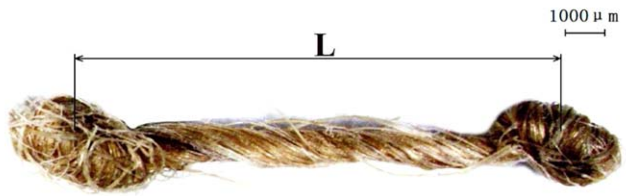

Figure 1. The bionic dumbbell-shaped jute fiber. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

reinforced with jute fibers of 3 wt %, 6 wt %, 9 wt %, and 12 wt % decreased with the decrease in temperature in cooling condition. The wear rates of the composite containing jute fiber were low at low temperatures and increased steeply with the increase in temperature. Dwivedi and Chand[30] evaluated the influence of fiber orientation on the friction and sliding wear behavior of polyester composite reinforced with jute fiber. The results showed that the coefficients of friction materials decreased with the increase in applied load; and the polyester composite reinforced with jute fiber may have great potential to apply in brake pad in future as friction material. Matějka et al.[31] reported the effect of jute fibers and powderized hazelnut shells as natural fillers in nonasbestos and nonmetallic organic friction composites. It was concluded that proper combination of natural materials can significantly improve the friction-wear properties of the prepared composites; and with respect to this observation, further research in the design and formulation of ecofriendly friction composites with natural plant materials could improve friction-wear properties of friction materials.

At present, most researchers studied the effect of treated fibers (treatments of alkalization, permanganate, peroxide and silane) on the friction and wear properties of the friction materials.[28] However, few researches had been reported about the effect of the structure design of jute fiber on the performance of friction material. In this study, the chemical property of jute fibers was modified by alkaline and the physical properties of the treated jute fibers were evaluated. In addition, these jute fibers were processed to have dumbbell-shaped structure and use as reinforced fibers. The effects of dumbbell-shaped jute fibers (DJFs) with different dumbbell-shaped spacing were systematically investigated, and the wear mechanism of the friction materials was discussed based on the morphologies of the worn surfaces obtained using the scanning electron microscopy (SEM).

EXPERIMENTAL

Preparation and Mechanical Testing of Jute Fibers

The jute fibers (*Corchorus capsularis* L.) were purchased from Fuzhou (Fujian Province, China). Before using them for the friction materials, jute fibers were modified in such way that they were firstly dipped into a mixture of HCHO and C_6H_6 (1 : 1) for 24 h at 25°C; those pieces were then kept in NaOH (17 vol %) solution for 2 h, rinsed with distilled water, neutralized with H_2SO_4 (2 vol %) for 30 min, and steeped in distilled water for 10 min at 25°C[32]; finally, the jute fibers were dried in an oven (JF980B, Changchun, China) at 140°C for 3 h.

The physical and mechanical properties of the jute fibers were tested using a tensile testing machine. The jute fibers for tensile tests were prepared with length of 40 mm and diameter of 0.5 ± 0.04 mm. The pulling speed of the tensile test machine was 100 mm/min during test. For the jute fibers, the measurements of the elongation at fracture, tensile strength, and elastic modulus were repeated and recorded five times.

Model of DJFs

The long bones of animals present dumbbell-shaped structure, which can not only buffer pressure outside but also transfer stress and have no special requirements for the interface strength. Based on the property of lime extremities of animals, the structure of jute fibers were processed to have this dumbbell-shaped structure and apply in the friction materials. The dumbbell-shaped spacing (L) was 5 mm, 10 mm, 15 mm, and 20 mm, respectively. The DJF is shown in Figure 1.

Preparation of the Specimens

The raw ingredients used for the friction materials and their mass fractions are listed in Table I. Jute fibers, compound mineral fibers and glass fibers were selected as reinforcing ingredients. Nitrile–

Table I. The Raw Ingredients Used for Friction Materials and Their Mass Fractions (wt %)

Raw materials	Manufacturer	Mass fraction
Compound mineral fiber	Beijing Hennian Technology & Trade Co.	15
NBR-modified phenolic resin	Jinan Shengquanhaiwosi Chemical Industry Co.	13
Vermiculite	Hebei Jinjian Mining Industry Co.	5
$BaSO_4$ (0.04–0.07 mm)	Henshui Zhongcheng Friction Materials Co.	19
Foam iron (0.2–0.4 mm)	Beijing Jinke Composite Materials Co.	11
Petroleum coke (0.3–0.8 mm)	Shanghai Taizhi Carbon Co.	6
Artificial graphite (0.3–0.8 mm)	Shanghai Taizhi Carbon Co.	8
Alumina	Jinan Shengquanhaiwosi Chemical Industry Co.	4
Antimony sulfide	Shanghai Danxu trade Co.	3
Friction powder	Haiyan Huaqiang Resin Co.	1
Glass fiber	Shenzhen Sailong Glass fibre Co.	9
Carbon black	Hebei Longxing Co.	3
Dumbbell-shaped jute fibers	Self-made	3

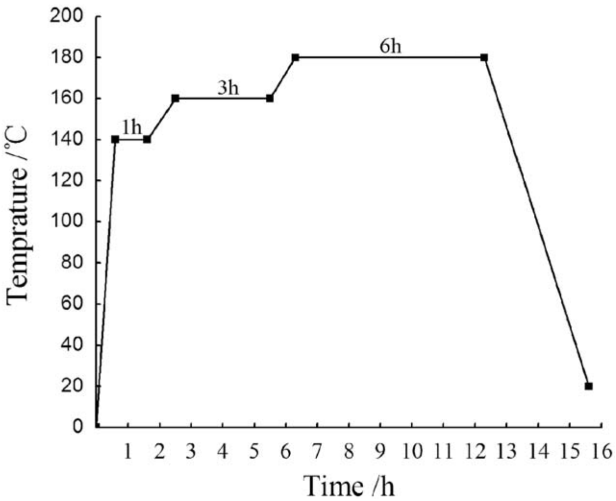

Figure 2. Heating process for preparation of friction materials.

butadiene rubber (NBR)-modified phenolic resins (Jinan Shengquanhaiwosi Chemical Industry Co., China) was used as a binder. Alumina and foam iron were used as an abrasive. Antimony sulfide, petroleum coke, carbon black, and artificial graphite were used as lubricants. Friction powder, vermiculite and $BaSO_4$ were used as particulate fillers. All raw materials were mixed carefully using a blender (JF805R, Zhuhai, China) for 10 min. Then the mixed materials were pressed by compression molder equipment (JFY50, Changchun, China) for 30 min at 160°C and pressure of 50 MPa. In order to ensure resin completely cured, eliminate the residual stress and remove a spot of residual volatiles, the mixed materials were dealt with heat treatment after hot pressing.[33] The post-treating material was segmented at 140°C for 1 h, 160°C for 3 h, and 180°C for 6 h continually in this study (Figure 2). Fifteen specimens with standard size of 25 mm × 25 mm × 6 mm were prepared for the friction and wear tests.

Friction and Wear Tests

The specimens were examined using friction material tester (JF150D-II, Changchun, China) with a constant speed (average linear sliding speed of 7.45 m/s) and pressure of 0.98 MPa according to the SAE J661 recommendation.[34] The rotating disc, which was made of cast iron (HT250) with hardness of HB180 to HB220, was used as counterpart. The schematic of friction-wear mode is shown in Figure 3. The rotating disc were heated to 100°C, 150°C, 200°C, 250°C, 300°C, and 350°C, and the friction coefficient (μ) and specific wear rate [$V(t)$, $mm^3/N{\cdot}m$] were measured accordingly during the friction tests. The volume wear rate was defined and calculated by the following equation:

$$V(t)=\frac{1}{2\pi R}\frac{A}{N}\frac{d_1-d_2}{f_m} \tag{1}$$

where R is the horizon distance between the centers of specimen and the rotating disk ($R=150$ mm), N is the number of rotation of the disk during tests ($N=5000$), A is the friction area of the specimen ($A=625$ mm^2), d_1 and d_2 are the average

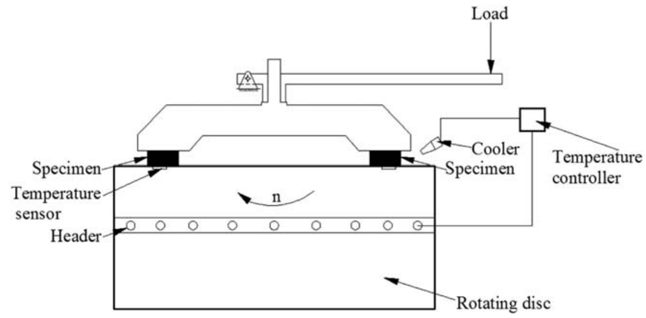

Figure 3. Schematic of friction-wear mode.

thickness of specimen before and after test, respectively, and f_m is mean value of the force due to sliding friction.

Density of each testing sample was measured using an electronic balance (MP-5002, Shanghai, China). Shear strength was measured using a universal testing machine (WAW-100, Changchun, China). After each test, the worn surface morphology of tested friction materials reinforced with jute fiber were characterized using the scanning SEM (JEOL5600; JEOL, Japan) at 25 kV.

RESULTS AND DISCUSSION

Physical Properties of Jute Fiber

The physical properties of jute fiber, such as strength, elongation, and elastic modulus, were firstly examined since they are related to the braking performance. The results show that the tensile strength and elastic modulus were increased by alkaline treatment (Table II). The tensile strength at fracture increased from 40.6 MPa to 67.4 MPa and the elastic modulus increased from 17.8 GPa to 25.3 GPa. While, the elongation at fracture decreased from 1.7% to 1.3%. These are because that the surface roughness of jute fibers was increased by alkaline treatment which could enhance the binding force between fibers and substrate in the friction materials.

Figure 4(a) shows the morphology of tensile fracture of the untreated jute fiber. The microfibril breakage and pullout of untreated jute fiber were the main tensile failure mode in the tensile process. It can be seen from Figure 4(b) that the rest of tensile failure mode showed brittle failure. The main tensile failure mode of the jute fiber treated with alkaline solution was debonding and had almost no microfibril breakage and pullout. This is because that some of the components, such as pectin which act as substrate between the microfibrils, were removed when the specimen was treated with alkaline solution. Therefore, these properties of jute fiber treated with alkaline solution will affect the friction materials.

Table II. Test Results of Mechanical Properties of Jute Fiber

	Elongation (%)	Tensile strength (MPa)	Elastic modulus (GPa)
Untreated jute fiber	1.7	40.6	17.8
Alkaline treated jute fiber	1.3	67.4	25.3

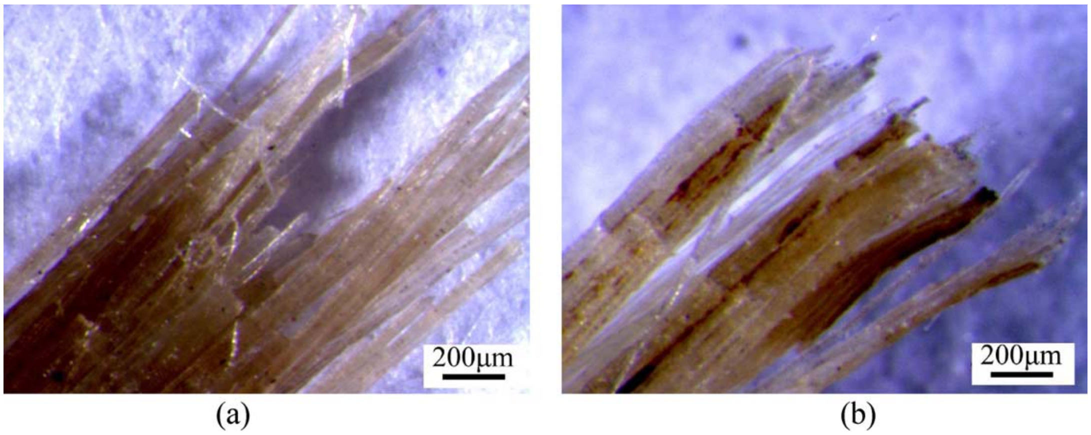

Figure 4. Morphologies of tensile fracture of (a) the untreated jute fiber and (b) the jute fiber treated with alkaline solution. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Mechanical Properties of the Friction Materials

Table III shows the mechanical properties of the friction materials. It was obvious that the density of the friction materials increased with the increase in the dumbbell-shaped spacing. The density of friction materials reinforced with straight jute fiber was the largest and that of the DJF with dumbbell-shaped spacing of 5 mm was the lowest. The shear strength increased at first and then decreased with the increase in the dumbbell-shaped spacing. The shear strength of the DJF with dumbbell-shaped spacing of 15 mm was the largest and that of the friction materials reinforced with straight jute fiber was the lowest. This is because that the DJFs in the fiction materials improved the interfacial strength between straight jute fibers and substrate.

Effect of the DJF on the Friction and Wear Properties of Friction Materials

Figure 5 shows the variation in the friction coefficients of the jute fiber-reinforced friction materials during the temperature-increasing procedure. Compared with straight fiber, the friction coefficient of DJF was relatively larger at 100–150°C, the friction coefficient of the DJF with dumbbell-shaped spacing of 10 mm were the largest at 100°C and the ones with dumbbell-shaped spacing of 15 mm were the largest at 150°C; the friction coefficient of DJF was relatively lower at 200–350°C, the friction coefficients of DJF with dumbbell-shaped spacing of 5 mm were the lowest at 200°C and 250°C and the ones with dumbbell-shaped spacing of 15 mm were the lowest at 300°C and 350°C. The friction coefficient of the DJF have some variation at 250°C, because the interfacial strength among jute fiber, glass fiber, and other fillers was reduced; meanwhile, jute fiber began

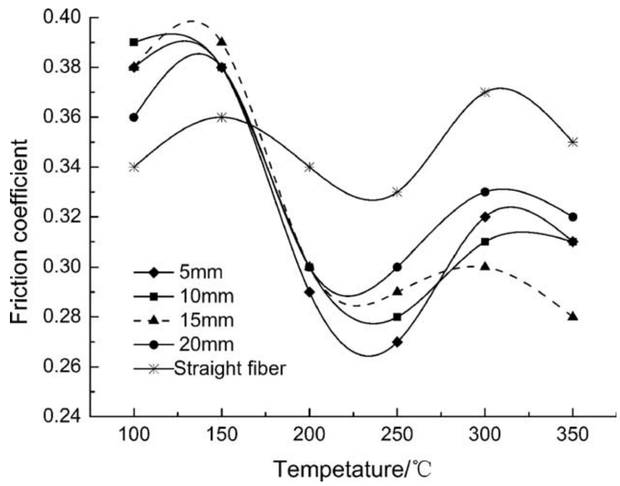

Figure 5. Variation in the friction coefficient of the jute fiber-reinforced friction materials with the temperature under temperature-increasing procedure.

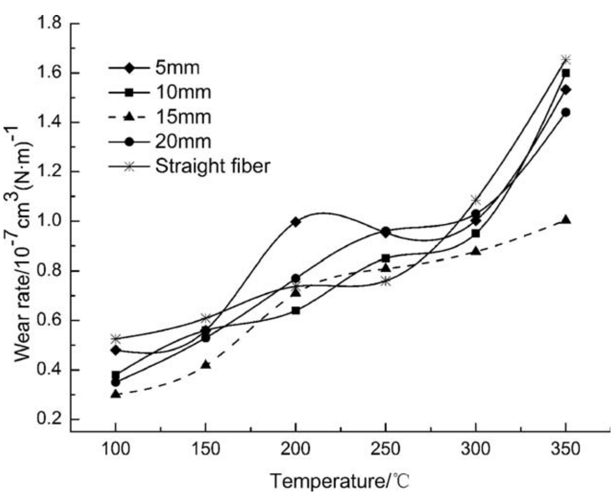

Figure 6. Variation in wear rate of the jute fiber-reinforced friction materials with the temperature.

Table III. Mechanical Properties of the Friction Materials

	Density (g·cm^{-3})	Shear strength (MPa)
5 mm	2.46	17
10 mm	2.59	28
15 mm	2.61	32
20 mm	2.63	21
Straight fiber	2.69	14

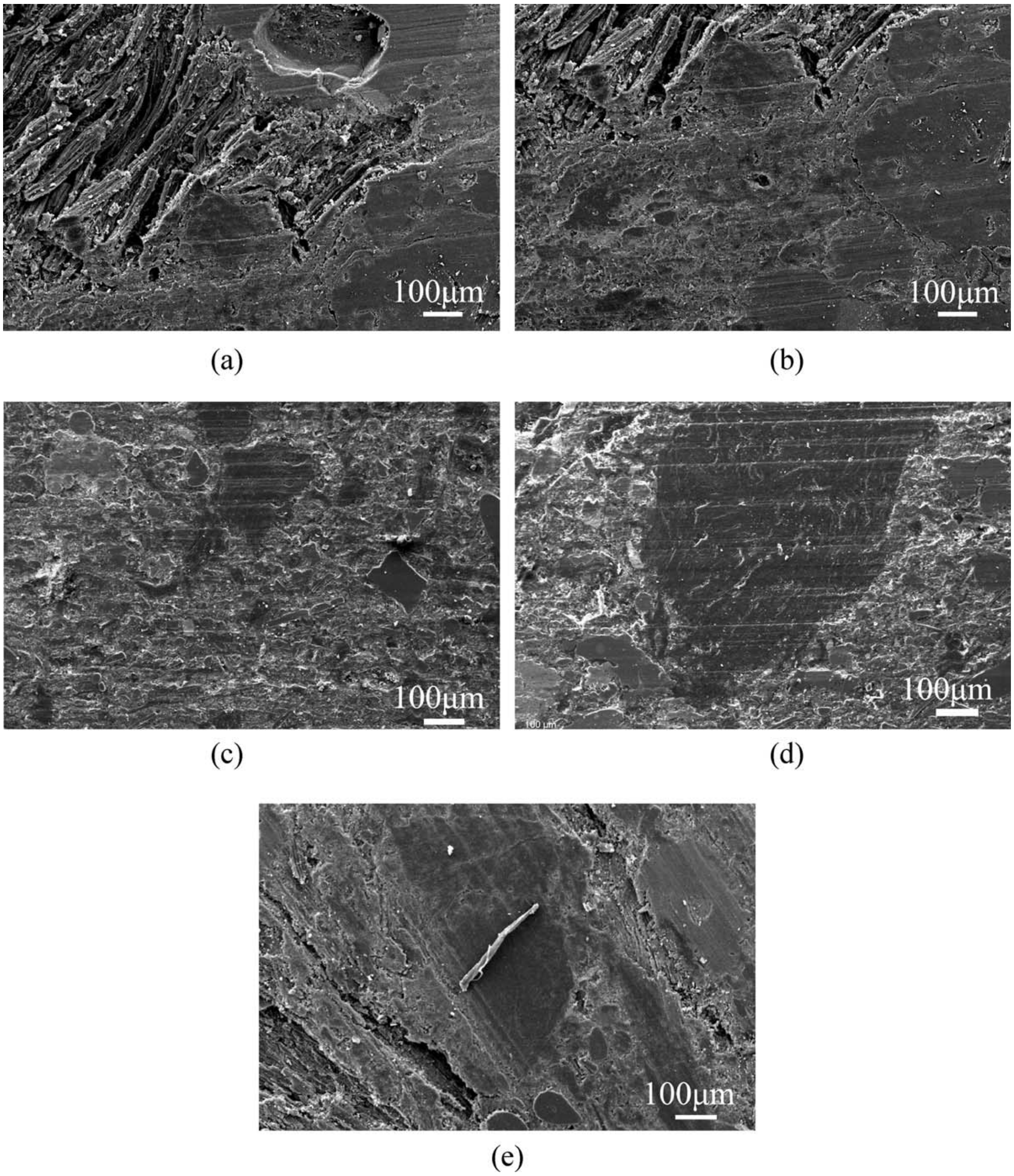

Figure 7. Surface morphologies of the jute fiber-reinforced friction materials with (a) straight fiber and dumbbell-shaped spacing of (b) 5 mm; (c) 10 mm; (d) 15 mm; and (e) 20 mm.

to decompose when surface temperature was higher than 250°C and much carbon powder appeared on the friction surface.

Figure 6 shows the variation in wear rates of the DJF with the temperatures. It can be seen that the wear rate of the DJF generally increased with the increase in temperature. The main reason is that the structure of the substrate of the friction materials began to change, the phenolic resins began to decompose and the jute fibers were carbonized gradually when the temperature increased. Compared with straight fiber, the wear rates of DJF were larger only at 200–250°C. This is because that the existence of the DJFs increased the compatibility between straight jute fibers and substrate. At high temperature (250–350°C), the wear rate of DJF was lower than that of straight jute fibers because the straight jute fibers were easily pulled out and carbonized. Conclusively, the wear rate of DJF with dumbbell-shaped spacing of 15 mm was the lowest, except for that when the temperatures were about 200–250°C. Compared with straight fiber-reinforced friction materials, the wear property of friction materials with dumbbell-shaped spacing of 15 mm was more superior. The presence of jute fiber with dumbbell-shaped spacing of 15 mm in the friction materials

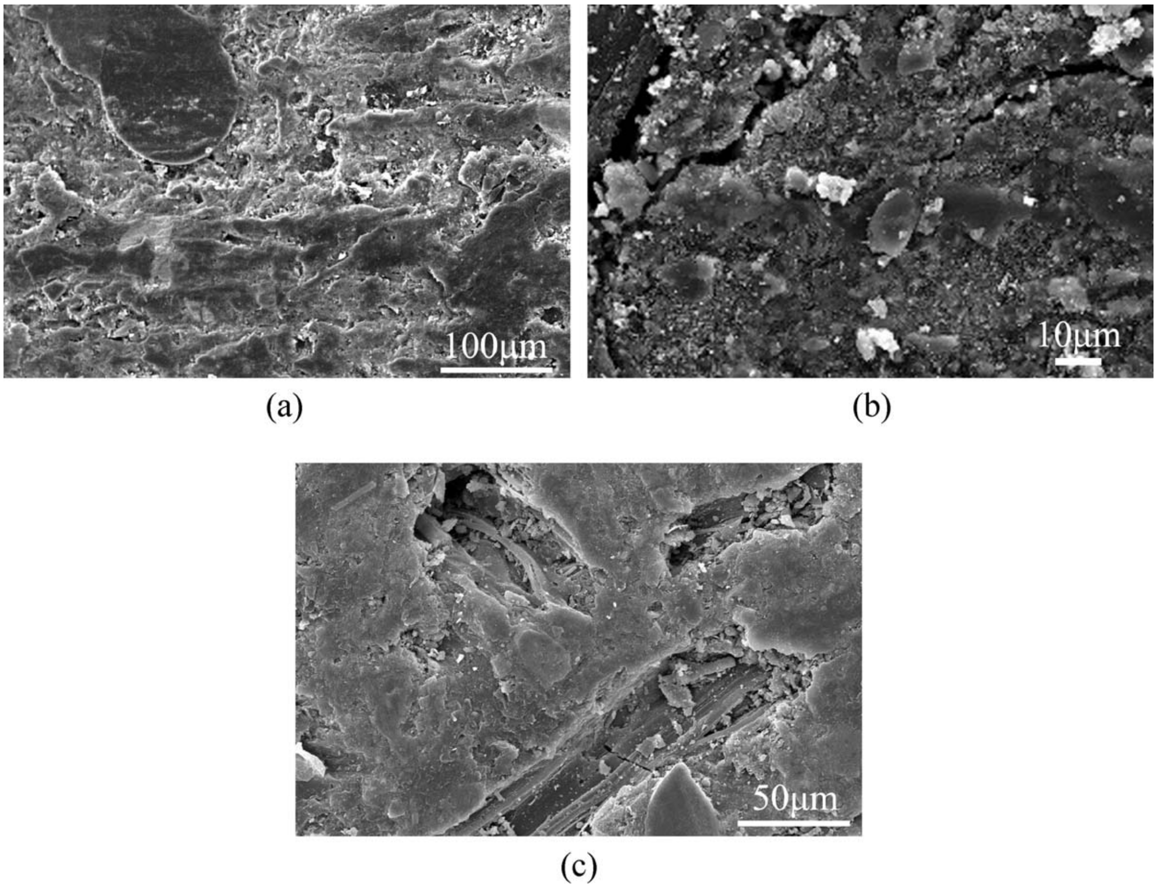

Figure 8. Morphology of the jute fiber-reinforced friction materials with (a), (b) straight fiber, and (c) dumbbell-shaped spacing of 20 mm.

leads to significant reduction of disc wear which indicates the variation reduction of disc thickness. The fact, that the variation in disc thickness caused by these friction materials was much lower, may possibly indicate that the friction materials when designed properly can potentially generate less noise, vibration and judder propensity.[35,36]

Effect of DJF on Worn Surface Morphology

The worn surface morphology of the friction materials can provide important information to reveal wear mechanism. The worn surface morphology of tested jute fiber-reinforced friction materials were characterized using SEM operated at 25 kV. The worn surfaces of samples tested at 350°C are shown in Figure 7. The scanning electron micrographs of Figure 7(a) shows typical worn surface of the straight jute fiber-reinforced friction materials. It indicates that the surface roughness was high and the adhesive wear and microcutting wear were serious. This is because that the straight jute fibers were carbonized and were easily pulled out by friction force. Therefore, the jute fibers lost the reinforcing effect and caused large grinding peelings dropped from the friction materials at high temperature (250–350°C).

The scanning electron micrographs of Figure 7(b–e) show typical worn surfaces of the DJF-reinforced friction materials, which indicate that the dumbbell-shaped spacing of jute fiber in friction material did not have much effect on the braking properties. However, compared with straight jute fibers, the surface of DJF was smooth, especially that of DJF with dumbbell-shaped spacing of 15 mm. The wear resistance of friction materials was affected both by the properties of the components and the interfacial adhesion between fibers and substrate.[37] The jute fibers with dumbbell-shaped spacing of 15 mm had excellent distribution in friction materials and improved the weak interfacial strength between straight jute fibers and substrate. Meanwhile, the DJFs were not easily pulled out and enhanced the wear resistance of friction materials, which is an alternative method for modifying the wear resistance of the jute fiber-reinforced friction material.[38] The results indicate that structure design of jute fibers is a simple, effective and environment-friendly method to enhance the interfacial adhesion between jute fibers and substrate.[39]

Wear Mechanisms of the DJF

In the friction and wear process, significant changes on the surface of the friction materials occurred with the increase in temperature. Some hard particles (such as those from glass fibers), ruptured and acted as abrasive of third body, were embedded on the surface of friction materials and then led to the ploughing phenomenon [Figure 7(c)] because the rotating disc was harder than the friction materials.

The morphology of the adhesive wear surface of friction material is shown in Figure 8(a). Some cold solder joint formed when the asperities on the wear surface were squeezed by heavy

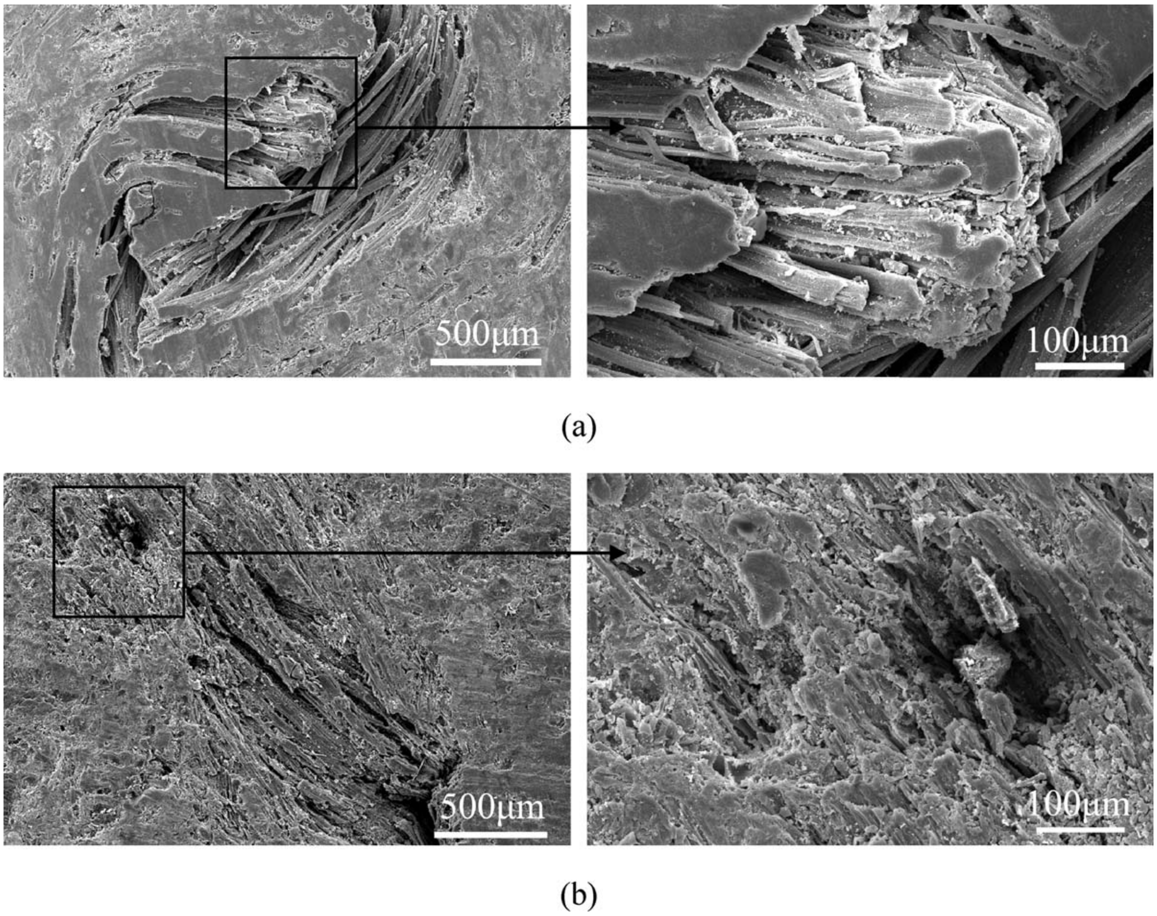

Figure 9. Morphology of jute fiber of the jute fiber-reinforced friction materials with (a) dumbbell-shaped spacing of 15 mm and (b) straight fiber.

load between friction material and rotating disc. Overheating occurred during the friction process. The cold solder joint was separated from the surface by friction force and caused that the adhesive wear appeared. At the same time, the compatibility between straight jute fibers and substrate were not strong enough to resist the repeated shear loading during wear process which led to crack. The morphology is shown in Figure 8(b). Crack initiation, growth, and coalescence took place in the sub-layer of the worn surface.[40]

At temperature of 350°C, the jute fibers were gradually carbonized, so the bonding force between fibers and substrate were affected seriously and the jute fibers were pulled out from wear surface, which could ultimately lead to the generation of grooves as shown in Figure 8(c). Some debris (such as abrasive particles of the glass fiber, mineral fiber, and carbonized jute fibers) exit in carbonization grooves on the friction surface, which helps to protect the bulk material from severe wear and markedly reduce the incidence of abrasive wear morphology. At the same time, the carbonized fibers can increase the carbon content on the friction surface, so the adhesive wear was decreased with the decrease in the friction coefficient.

Morphology of Jute Fiber of the DJF

The function of jute fibers in the friction materials not only provides high friction coefficient, but also reinforces the interfacial strength of substrate of friction material. The failure modes of jute fibers were carbonization [Figure 8(c)], tensile failure [Figure 9(a)], and surface abrasion [Figure 9(b)]. The interfacial strength between fibers and substrate were affected seriously at high temperature (250–350°C), so the jute fibers were pulled out from wear surface, which could ultimately lead to grooves. The jute fibers in axial direction paralleling to the friction direction were mixed with substrate, improved the performance of friction materials. The existence of the dumbbell-shaped structure plays an important role in improving the interfacial strength between jute fibers and substrate so that the jute fibers were not easily pulled out. However, sometimes, tensile fracture of the carbonized jute fibers partially occurred under friction force and the fracture surfaces presented brittle failure [Figure 9(a)]. It can be found from Figure 9(b) that the jute fibers had been carbonized and the wear of straight jute fiber was quite serious because that the asperities on the wear surface were squeezed and slid by heavy load when the temperature increased during the wear process.

Morphology of Glass Fiber of the Jute Fiber-Reinforced Friction Materials

Figure 10 shows the morphology of glass fiber of the DJF. The glass fiber got thinner in radial direction. It was then ruptured to hard particles and embedded on the surface of friction pairs,

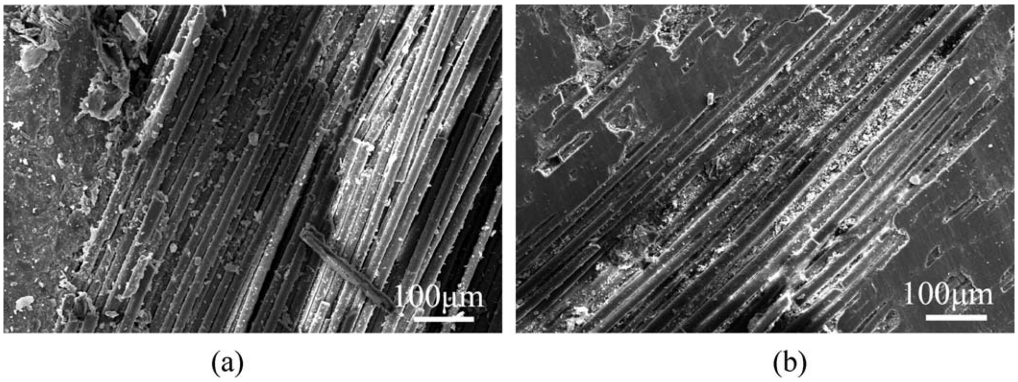

Figure 10. Morphology of glass fiber of the jute fiber-reinforced friction materials with (a) straight fiber and (b) dumbbell-shaped spacing of 10 mm.

so the friction force increased.[41] It can be seen from Figure 10(a) that the wear of the straight jute fiber-reinforced friction materials was quite serious and the bare glass fibers were pulled out. However, the glass fibers being pulled out were not obvious on the surface of the DJF, only with mild wear and some voids [Figure 10(a)]. The voids existing on the friction surface can absorb the braking noise in certain degree.

CONCLUSIONS

The effects of DJFs on the friction performance of friction materials were investigated in this study. The results can be summarized as followed:

1. Jute fibers have strong physical and mechanical properties, especially when the jute fibers were treated with alkaline solution.
2. Compared the straight fiber-reinforced friction materials, the friction coefficient of the DJF-reinforced friction materials had greater fluctuation and they were relatively large at low temperature and slightly smaller at high temperature.
3. The wear rate of the DJF with dumbbell-shaped spacing of 15 mm was the lowest, except for that when the temperatures were about 200–250°C.
4. The DJFs in the fiction materials improved the weak interfacial strength between straight jute fibers and substrate. Meanwhile, the DJFs were not easily pulled out which enhanced the wear resistance of friction materials. Compared with straight fiber, the worn surface of DJFs with dumbbell-shaped spacing of 15 mm reinforced in the friction materials was smoother. It only exists some ploughed furrows and a small number of microporous.

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