Effects of vermiculite on the tribological behavior of PI-matrix friction materials

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Abstract. Effects of vermiculite as a friction modifier on brake friction performance of PI-matrix materials have been tested. PI-matrix friction materials with different vermiculite content (0%, 5%, 10%, 15%, 20% in wt) were prepared by the heat-press molding method. The friction tests were carried out on a pin-on-disk tester in the speed range of 20~120 km/h. The experimental results indicate that the effects of vermiculite on the friction and wear performance of the materials are closely related to the friction speed. At low friction speeds (between 20~40 km/h), the friction coefficient increases with the increasing of vermiculite content. At high friction speeds (between 60~120 km/h), the friction coefficient increases at first when vermiculite content below 10 wt% and then decreases with vermiculite content increasing. The wear rate decreases by adding 5 wt% vermiculite, and then increases. As the friction speeds above 100 km/h, the wear rate changes dramatically.

1. Introduction

The friction materials used in the brake system should have stable and reliable coefficient of friction (COF) at wide range of braking load, friction speed, service temperature, humidity, and so on [1]. These characteristics accompanied with high wear resistance, low noise, light weight, acceptable cost and easy processing make a friction material ideal for the brake system. The polymer-based composite materials have been known to be the best candidate to serve as friction materials in the brake system.

The performance of the friction material is strongly affected by the selection of the ingredients. The number of ingredients used for formulation of such composites may exceeds 700, and they can be mainly classified into four prime classes; namely binder, fibers, fillers, and friction modifiers [2–4]. The binder (such as phenolic resin and rubber) binds the ingredients firmly so that they can perform the desired function in the friction materials [3]. Ideally, there should be no significant deterioration in the function of the binder when the brake is operated under diverse conditions. The fibers play a major role in maintaining strength, stiffness, thermal stability, and frictional properties of the composite such as organic and mineral fibers (aramid pulp, oxidized polyacrylonitrile fiber, acrylic, cellulose, carbon, glass and slag fibers, wollastonite). The fillers are low-cost minerals (such as barite and clay) whose primary role is to increase the volume of the friction material and thus to cut the overall cost of a

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composite on a volume basis. The friction modifier's roles is the alteration of the friction behavior, which are classified into two kinds: abrasives, for example aluminum oxide (Al_2O_3), zircon ($ZrSiO_4$), zirconium oxide (ZrO_2), and silicon carbide (SiC) with Mohs hardness values of about 7–9 and lubricants, such as graphite, coke, MoS_2, and Sb_2S_3 and so on [5].

Vermiculite is one of important minerals with lamellar structure composed of two silica tetrahedral sheet. Vermiculite has the advantages of low density, low hardness, low thermal conductivity and good thermal stability, strong sound-absorbing. Vermiculite can take place of asbestos in the field of friction materials. As the cohesive force of vermiculite between interlayer is weak, and the structural characteristics of infinite lax and dispersion, vermiculite can closely be connected with the matrix. Thus the friction materials containing vermiculite have high bonding strength and resistance to shear stress [6]. The hardness of vermiculite is low (Mohs hardness values between 1 ~ 1.5). However, vermiculite can increase the friction coefficient under certain conditions for the lamellar structure. Cao et al. [7, 8] developed a new friction composite reinforced with flake vermiculite, and the results indicated the flake vermiculite has good reinforcing properties; Zeng et al. [9] confirmed the feasibility of vermiculite taking place of asbestos fiber.

The friction process is always accompanied by the development of debris (the third body) [10], which adheres to the rubbing couple. As a result, the characteristic friction layers form on the friction surface, which determines friction performance. The characterization of friction layer differed with the friction conditions and the component of the friction materials. The purpose of this study is to evaluate the effects of vermiculite as friction modifier on friction performance and friction layers of PI-matrix materials. Some insights into the friction and wear mechanism of the friction materials are provided.

2. Experimental

2.1. Fabrication of the samples

The investigated friction materials contain different ingredients including resin (table 1), reinforcing fibers (wollastonite 10 um), solid lubricant (graphite, 314~400 um), abrasive (iron powder EPA-512), fillers (barite 44 um) and friction modifier (vermiculite 44 um and friction powder FB-80. All the ingredients were well mixed, then PI-matrix materials were prepared by the heat-press molding method at heat-press temperature 220℃ under heat-press pressure of 8 KN for 40 minutes. The obtained samples were cylindrical of ϕ16 mm×20 mm. Then the friction materials were post-treated at 120℃ for 60 minutes, at 150℃ for 60 minutes, and at 180℃for 120 minutes.

Table 1. The compositions of the designed samples (in wt %).

ingredients	Samples				
	1	2	3	4	5
PI	10	10	10	10	10
Wollastonite	8	8	8	8	8
Graphite	18	18	18	18	18
Friction powder	10	10	10	10	10
Iron powder	7	7	7	7	7
vermiculite	0	5	10	15	20
barite	37	32	27	22	17
others	10	10	10	10	10

2.2. Tests of friction performance

The tribological properties were tested on a pin-on-disk tester (see in figure 1). The disk is made of H13 steel, and the diameter of the friction is 150 mm. The friction interface pressure is 0.57 MPa, The friction rotating velocity is 200~3000 r/min (11~170 km/h), the friction time was 90s under each friction speed; the microstructures were observed optical microscopy (OLS 3000) and JSM−6360LV scanning electron microscopy (SEM).

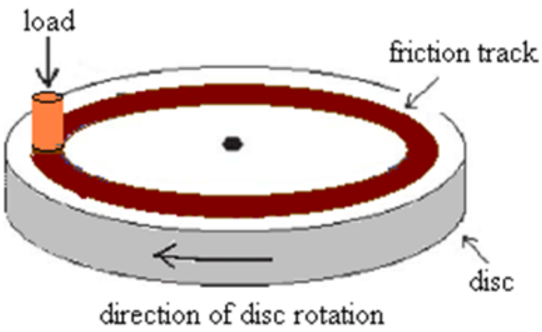


Figure 1. Schematic of the pin-on-disk tester.

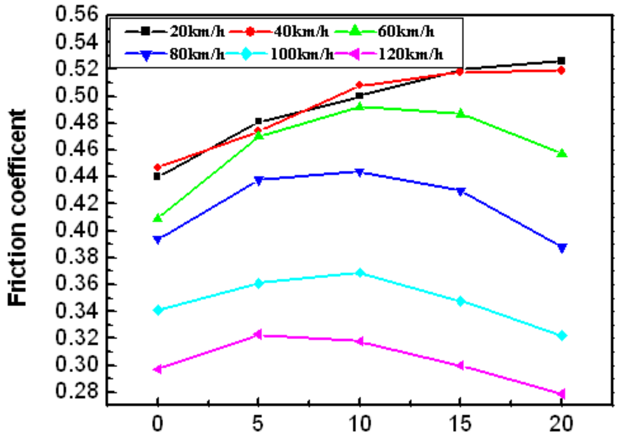


Figure 2. Effect of vermiculite content of friction coefficient of the friction materials.

3. Results and discussion

3.1. Effect of vermiculite content on the friction coefficient of the friction materials

The dependence of the vermiculite content, on the average friction coefficient of PI-matrix friction materials at different friction speed are shown in figure 2. The friction coefficient increases with vermiculite content increasing at the friction speeds between 20~40 km/h. When the friction speeds between 60~120 km/h, the friction coefficient increases to the maximum value at the content of vermiculite between 5~10 wt% and then decreases.

The friction force results from the mechanical action and intermolecular force between the two friction surfaces. A large amount of micro peaks or valleys on the friction surface are unavoidable. The micro peaks are generally referred to as asperities. The mechanical force included actions, such as the micro peaks and valleys meshed with each other, leading to deformation, shearing, breaking, and the asperities embedded into the dual surface as a result of ploughing on the friction surfaces, and so on. As the cohesive force of vermiculite between layer is weak, and the structural characteristics of infinite lax and dispersion, vermiculite can be closely bond with the matrix when the amount to be optimized because of the interlayer structure of vermiculite. The friction torque increases and the friction coefficient increases with the increasing of vermiculite content (below 10 wt. %).when the concentration of vermiculite is above 10 wt%, the cohesive force between PI and vermiculite decreases, stripping and drawing cause the friction torque to decrease. As a result, the friction coefficient decreases.

With friction speed increasing, the impact and shear force between asperities in the dual friction surface rapidly increase, so that a lot of debris are formed by shearing and ploughing. Under the effect of friction pressure, the debris fill the gap between peaks and valleys, thereby the ploughing effects of the asperities are reduced. As the friction speed increases, the temperature on the friction surface is likely to be very high, which induced the matrix closed to the friction surface to be oxidized and carbided, and the compressive and inter-laminar shear strength closed to the friction surface to be lowered, which make more debris be produced, leading a increased areas of friction surface covered by the debris. Finally, a continuous friction film is formed on the friction surface, resulting in the decreasing of friction coefficient. Schematic illustration of the filled debris and the formed friction film is shown in figure 3 [11].

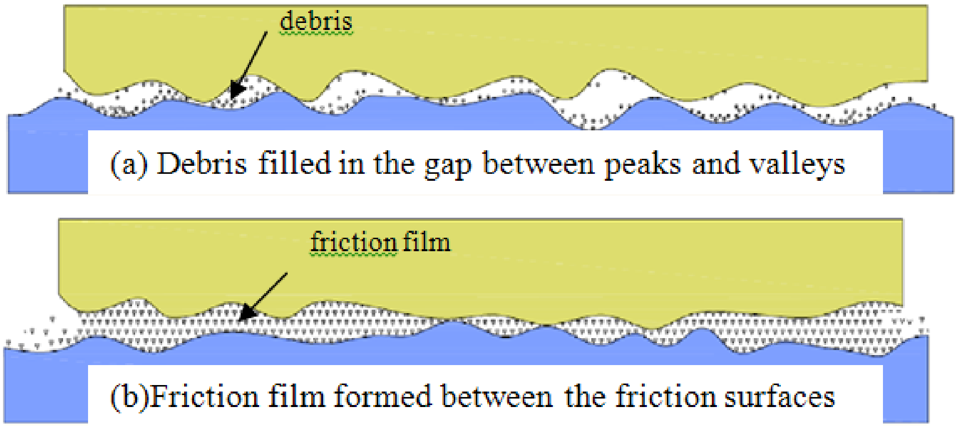


Figure 3. Schematic illustration of the debris filled and the friction film formed.

3.2. Effect of vermiculite content on wear rate of the friction materials

The relationships between the wear rate and the content of vermiculite at different friction speed are shown in figure 4. The wear rate increases slowly with the increasing of friction speed below 80 km/h. However, the wear rate increases rapidly as the friction speed above 80 km/h. There are possibly two reasons: 1, high friction speed results in a great impact and shear force between asperities in the friction surface, and then a great deal of debris are produced, which increases the wear rate; 2, the temperature on the friction surface is likely to be very high, which induce the matrix closed to the friction surface to be oxidized and carbided, and the compressive and inter-laminar shear strength closed to the friction surface to be lowered, which make the wear be aggravated with the speed increasing [12].

Figure 4 shows that the wear rate decreases at first and then increases with the increasing of vermiculite content. The effects of vermiculite content on wear rate of the friction materials are related to the friction speed. At the low friction speed, the wear rate changes a little. As the friction speeds above 100 km/h, the wear rate changes dramatically. When the content of vermiculite is 5 wt%, the wear rate is lowest at all friction speed. Because the cohesive force between vermiculite and PI matrix is high; the specific surface area of layered vermiculite is large; the layered vermiculite has lots of pore, which can adsorb lots of water and small molecular compounds decomposed from PI- matrix of the friction materials [9]. As a result, the wear rate decreases. When the content of vermiculite is above 10wt%, the PI-matrix cannot bond all the sheet of vermiculite well. Vermiculite is easily peeled off from the matrix, and the wear rate increases rapidly.

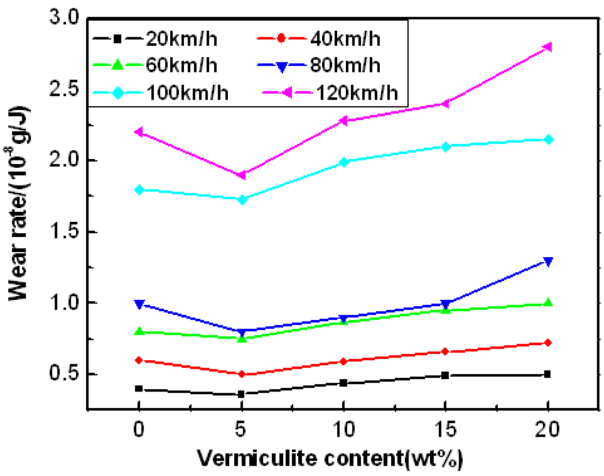


Figure 4. Effect of Vermiculite contents on wear rate of the friction materials.

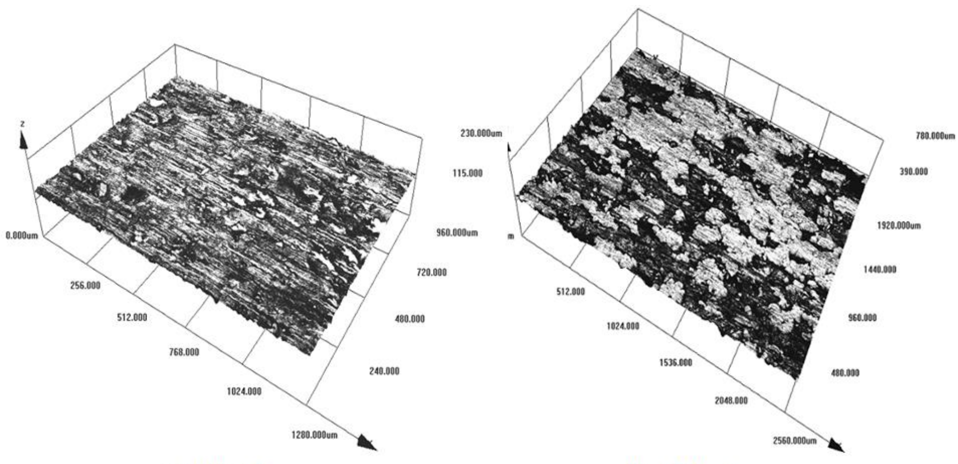
3.3. The morphology of friction surface

In order to study the role of vermiculite in PI- matrix of the friction materials, the friction film and debris under the friction speeds 20km/h and 120km/h have been shown in figures 5 and 6. Character of the friction layer determines the friction performance. It can be seen from figures 5(a) and 6(a) that the worn surface is uneven with many grooves and wear debris distributed on it at the speed of 20 km/h. Figure 6(b) shows the morphology of debris collected at counter friction surface at the friction speed of 20 km/h, which are small and equiaxial particles. At the friction speed of 120 km/h, it can be seen from figures 6 and 7 that a continuous friction film by the main constitution of vermiculite is formed on the friction surface, and the friction surface is flat, as shown in figures 5(b) and 6(c). Figure 6(d) shows that the debris collected on the counter surface are big sheets, which are quite different from the figure 6(b) at 20 km/h. At low friction speed, the friction force partly comes from the force shearing the flake vermiculite into smaller particles, so the friction force increases as the rising content of vermiculite. As a result the friction coefficient increases at low friction speed. With the braking speed increasing, the impact and shear force between asperities in the dual friction surface increase rapidly. The lamellar vermiculite peels off, which need to overcome the cohesive force of vermiculite between interlayer, so the friction coefficient of friction materials containing vermiculite between 5~10wt% is higher compared with the non-vermiculite friction material. When the content of vermiculite up to 10 wt%, the friction coefficient decreases rapidly with the friction speed rising. Because the impact and shear force increase continuously and the temperature maybe high with braking speed increasing, the PI-matrix cannot bond all the sheet of vermiculite well, vermiculite is easily peeled off from the matrix. And the hardness of vermiculite is low. The vermiculite peeled off can play the role of lubrication, so the friction coefficient decreased.

4. Conclusions

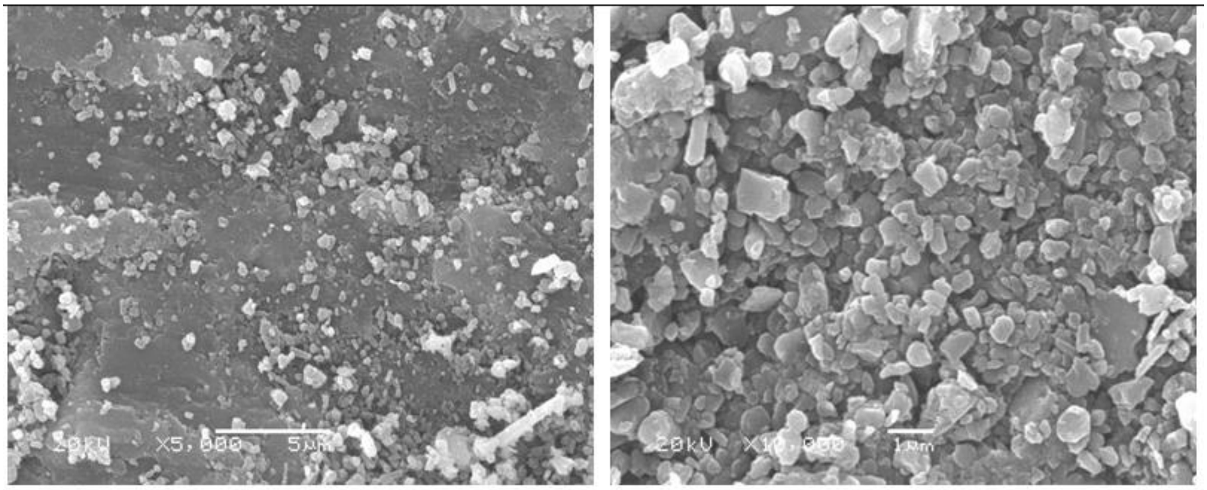
The effects of vermiculite content on friction performance were comprehensively evaluated. The effects of Vermiculite content on the friction and wear performance of the materials are closely related to the friction speed.

- At low friction speeds (between20~40km/h), the friction coefficient increases with the increasing of Vermiculite content.
- At high friction speeds (between 60~120km/h), the friction coefficient increases and then decreases with the increasing of Vermiculite content. The friction coefficient increases when the content of vermiculite between 5wt%~10wt%. With friction speed increasing, the impact and shear force between asperities in the dual friction surface increase rapidly. So that the flake vermiculite drops off, which need to overcome the cohesive force of vermiculite between interlayer. When the content of vermiculite is up to10 wt%, the friction coefficient

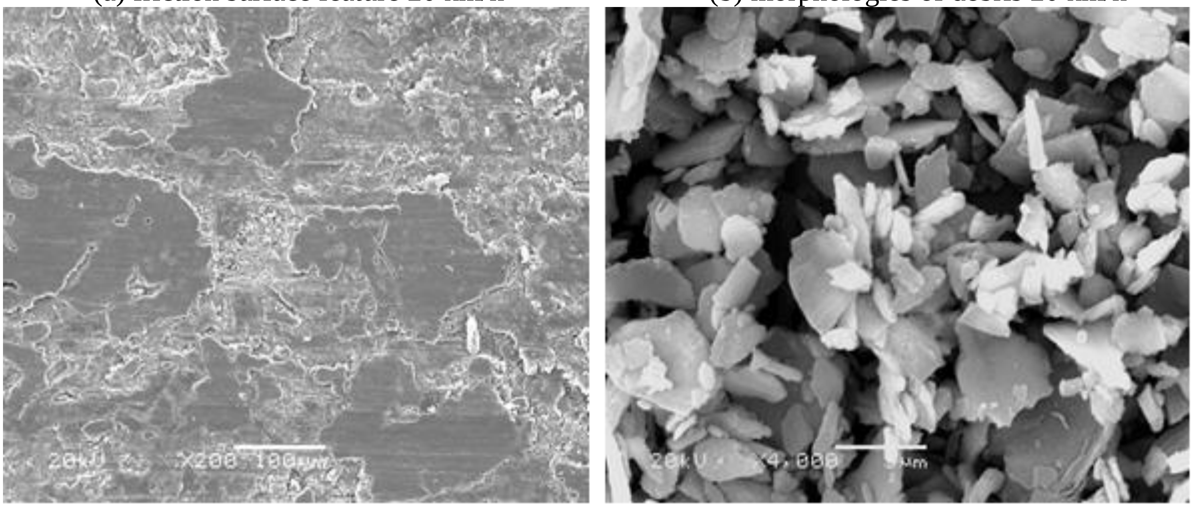


(a) 20km/h (b) 120km/h

Figure 5. The 3－D morphology of friction surface at different friction speeds.



(a) friction surface feature 20 km/h (b) morphologies of debris 20 km/h



(c) friction surface feature 120 km/h (d) morphologies of debris 120 km/h

Figure 6. Morphologies of friction surfaces and debris at different friction speeds.

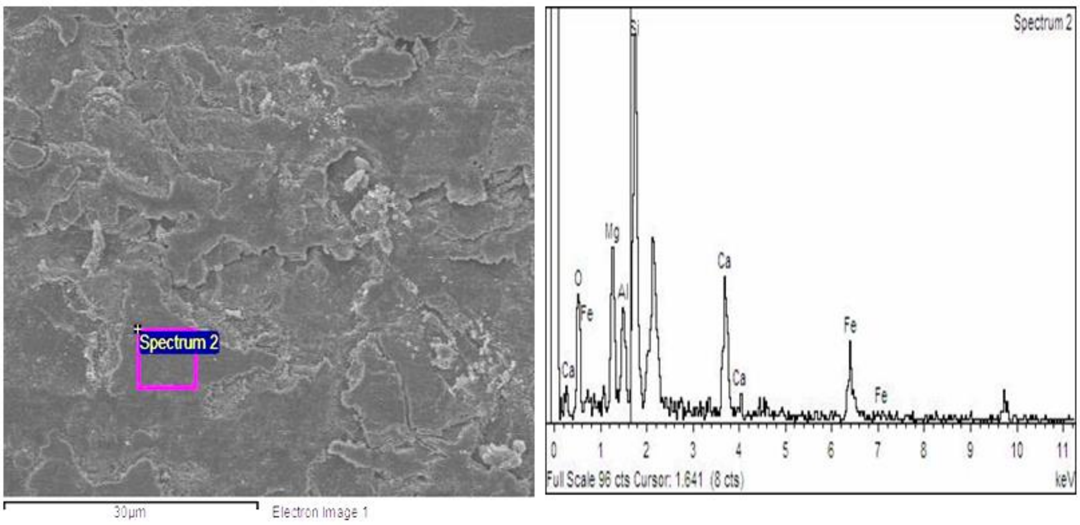


Figure 7. The spectrum of the continuous film at friction speed of 120 km/h.

decreases rapidly with the friction speed rising, because the PI-matrix cannot bond the vermiculite well.

- The wear rate decreases at first and then increases with the increasing of vermiculite content. As the friction speeds above 100 km/h, the wear rate changes dramatically
- The content of Vermiculite is about 5wt. %, The friction coefficient of the friction material is relatively stable, and the wear rate is low, the friction material shows good friction and wear performance.

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