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Friction and Wear Behaviors of Porous Paper-Based Friction Pairs in Wet Clutches by Pin-on-Disc Tests

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Abstract **-** To investigate the friction and wear behaviors of porous paper-based friction material in wet clutches under severe working condition, the dry pin-on-disc tests were carried out by a UMT-5 tribometer. The test results of COF are presented, and the coefficient of variation is calculated and analyzed. To reveal the high temperature wear mechanism of paper-based friction material, the microstructure of worn surfaces is analyzed. The wear mechanism and friction behaviors of paper-based friction material are influenced by the softening, carbonization, and oxidation of fibers and resin. This investigation of friction and wear behaviors under dry working condition can be used to simulate the engagement process and explain the nonuniform wear phenomenon of wet clutches in SAE#2 tests.

Keywords**:** Paper-based friction material; Pin-on-disc test; Friction coefficient; Friction film; Wear mechanism

1. Introduction

The paper-based friction pairs are widely used in the multidisc wet clutches in the transmission system of commercial and civil cars. The paper-based friction material has porous microstructure, enabling the lubricant to reach the contact interface and providing lubrication. As power shift and torque transfer devices, wet clutches frequently work under extremely poor working conditions, for instance, high initial relative sliding velocity, high surface pressure, and high temperature rise. It is essential to investigate the frictional performance of friction pairs to optimize the design of wet clutches and improve the performance of vehicle.

Lots of numerical and experimental research have been done to investigate the friction and wear behaviors of wet clutches. Gao et al. [1], Li et al. [2], Ompusunggu et al. [3], and Iqbal et al. [4] presented numerical models and experiments to investigate the engagement process of wet clutches. At the initial phase of engagement, friction discs are separated from the separate discs and rotate with relative velocity. Then, the asperity contact occurs and the relative velocity rapidly decreases. During the engagement process, a lot of heat is intensively generated in a short time, at the same time, the interface temperature of friction pairs rises rapidly. Lingesten et al. [5] reported an interesting two-stage wear rate phenomenon of wet clutches based on a huge number of engagement cycles. Then, Li et al. [6] developed a methodology to predict the two-stage wear rate of the friction lining according to engagement cycles. Fernandes et al. [7] investigated the transition from mild wear to severe wear when a brake friction material pin against a perlitic cast iron disc under dry conditions. It was observed that the transition from mild to severe wear was controlled by the breakage of the friction film. Further, Fernandes et al. [8] carried out pin-on-disc tests by stand process and cleaning the wear debris. It was observed that the friction film was not beneficial to keep high COF. Ompusunggu et al. [9] investigated the effect of adhesive wear and thermal degradation on the dry friction behaviors of paper-based friction material against steel. Fei et al. [10] investigated the friction behaviors and thermal degradation of carbon fiber reinforced paper-based friction material with different phenolic resin contents. The thermal degradation of the paper-based friction material had three stages, which were 250-370℃, 370-600℃, and 600-850℃, and the maximum mass loss happened in stage two due to the carbonization and oxidation of resin and fibers. Zhao et al. [11] investigated the friction and wear behaviors of Cu-based friction material by pin-on-disc tests, and the high temperature wear mechanism was analyzed.

A wet clutch which contains three paper-based friction discs and four 65Mn steel separate discs has been tested using SAE#2 test rig under mild and severe working conditions. The picture of the middle friction disc is shown in Fig. 1, meanwhile, the microstructure of three points a, b, c is shown in Fig. 2. It is clear that the wear is different in radial direction, in other words, the wear of the middle radius area is more severe. We consider that the high frictional heat generated in the clutch engagement process has led to the failure of the lubricant film under the severe working condition. And the high temperature could cause the carbonization of lubricant oil and fibers, decreasing the porosity of friction material. After lubricant film failing, a part of the friction interface could work on dry conditions. Therefore, nonuniform wear appeared in the friction pairs. To accurately simulate and further explain the phenomenon above, the friction and wear behaviors of paper-based friction material under dry working conditions have to be completely investigated.

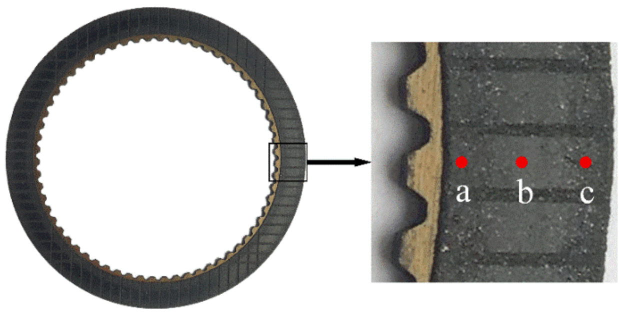

Fig. 1: The second friction disc after SAE#2 tests.

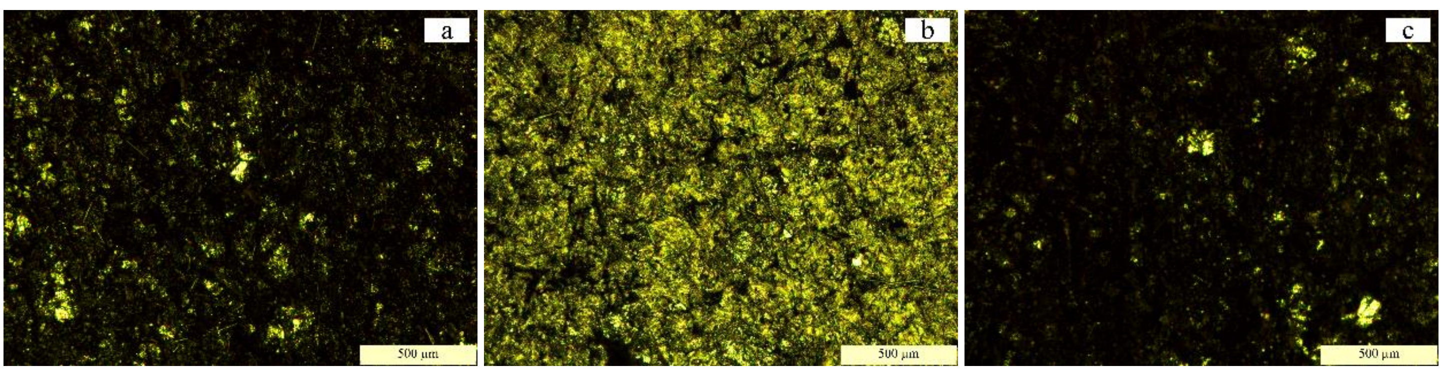

Fig. 2: SEM micrographs in different radial positions: (a) inner; (b) middle; (3) outer.

In this paper, the friction and wear behaviors of paper-based friction pairs are investigated by pin-on-disc tests, and there is no lubricant present during these experiments. The tribometer, materials, and test procedure are introduced in Section 2. The test results are presented in Section 3, furthermore, the fluctuation of COF and the wear and failure mechanisms of paper-based friction material are respectively discussed. This paper ends with the summary and conclusions in Section 4.

2. Experimental procedure

2.1. Equipment

The tribological tests were carried out in the laboratory on a UMT-5 pin-on-disc tribometer. The structure and key modules of the tribometer are shown in Fig. 3. The tribometer includes elevated temperature chamber for rotary drives, temperature display module, force sensor module, and data acquisition module.

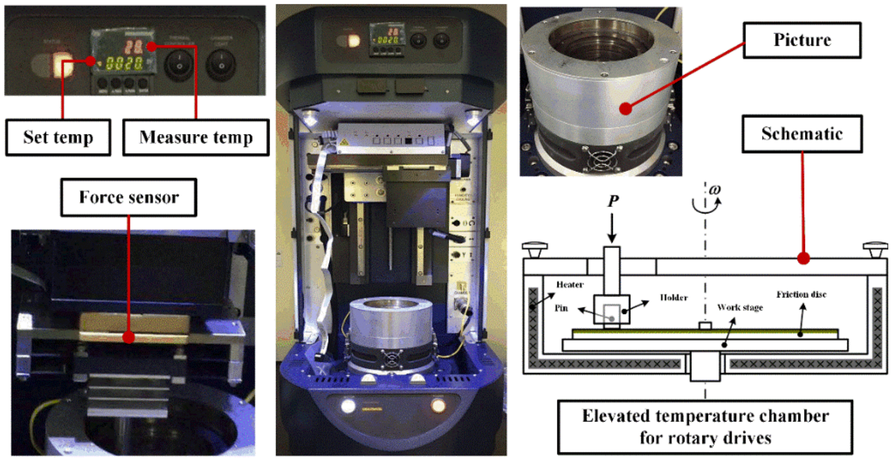

Fig. 3: Structure of the pin-on-disc tribometer.

The heating range of the elevated temperature chamber is 0-400℃ with a ±4℃ control accuracy. The velocity range of the rotary work stage is 0.001-5000r/min. The force sensor accurately measures the dynamic change of forces in x, y, z direction, namely, the tangential force, the radial force, and the normal force. The COF is calculated by the following equation.

$$COF=\sqrt{F_x^2 / F_z^2} \tag{1}$$

2.2. Materials

The materials of the friction pair used in the pin-on-disc tests are the same as the SAE#2 tests. The friction disc, which consists of porous paper-based friction lining with a thickness of 2mm and a baseplate made by 65Mn steel with a thickness of 4mm, is shown in Fig. 4. The diameter of the steel pin is 6mm, and the rotation radius on the friction disc is 25mm. During the test, the pin was fixed with the force sensor module, and the friction disc was fixed with the rotary work stage.

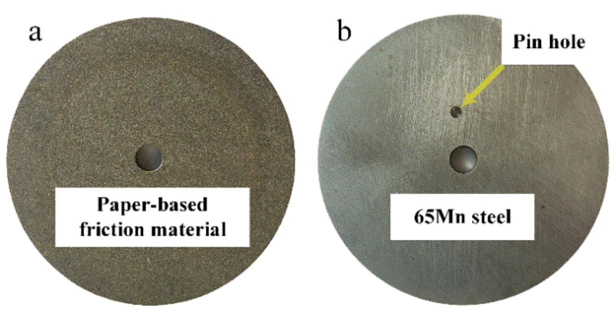

Fig. 4: Pictures of the friction disc: (a) front side; (b) reverse side.

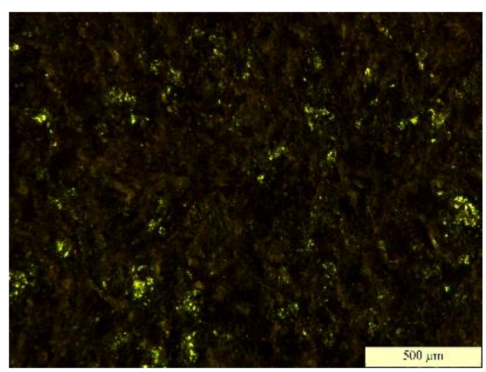

Fig. 5: SEM micrograph of unworn surfaces.

The paper-based friction material contains modified phenolic resin as the matrix and binder, synthetic and cellulose fibers, and fillers as friction modifiers. The microstructure of the unworn material surface is shown in Fig. 5, the bright spots on the surface are uncovering binder, and the dark area is fibers and fillers.

The physical characteristics of the materials in the friction pair are shown in Table 1. The elasticity modulus and the heat conductivity of the paper-based friction material are obviously smaller than that of 65Mn steel.

Table 1: Physical characteristics of the materials.

Parameters	65Mn steel	Paper-based friction material
Elasticity modulus (GPa)	160	0.27
Density (kg/m^3)	7800	1125
Specific heat capacity (J/kg·K)	487	1610
Heat conductivity (W/m·K)	45.9	0.241
Poisson's ratio	0.3	0.12

2.3. Tribological Tests

In order to respectively investigate the influence of velocity, load, and temperature on the friction performance of paper-based friction material against 65Mn steel, the velocity range was set from 26mm/s (10r/min) to 5236mm/s (2000r/min), and the load range was set from 0.7MPa (20N) to 4.2MPa (120N), and the temperature range was set from 25℃ to 400℃. The operating parameter settings in pin-on-disc tests are shown in Table 2.

Table 2: Operating parameter settings in pin-on-disc tests.

Load/Temp	Velocity(mm/s)/ Rotation speed(r/min)	Temp/Velocity	Load(MPa)/ Normal force(N)	Velocity/Load	Temp(℃)
2.1MPa 175℃	26(10)	175℃ 1309mm/s	0.7(20)	1309mm/s 2.1MPa	25
	262(100)		1.4(40)		100
	1309(500)		2.1(60)		175
	2618(1000)		2.8(80)		250
	3927(1500)		3.5(100)		325
	5236(2000)		4.2(120)		400

All the friction pairs had been run in under same working condition before test, and when the friction coefficient was stable after running in, the test was started. When the temperature stabilized at the target temperature, the test procedures were carried out: (1) Pressing the pin against friction disc; (2) Bringing the electromotor to the target rotation speed; (3) Recording the rotation speed, load, temperature, and COF; (4) Stopping the electrometer and separating the pin and friction disc; (5) Replacing the pin and friction disc for next test. The test duration after running in was 300 seconds.

3. Results and Discussion

In order to investigate the friction and wear behaviors of paper-based friction material under dry working conditions influenced by different velocities, loads, and temperatures, the test results presented below are carried out with six different velocities, six different loads, and six different temperatures, respectively. The friction coefficient, fluctuation of COF, and wear mechanism will be primarily analyzed in this part.

3.1. Friction Coefficient

Fig. 6a shows the test results of COF under different velocities and Fig. 6b presents the average friction coefficient of paper-based friction pairs. It is clear that the paper-based friction material has different friction characteristics under low and high velocities. As the velocity rises from 26mm/s to 262mm/s, the average friction coefficient decreases sharply from 0.318 to 0.135, the decrease range of which is about 57%. As the velocity rises from 262mm/s to 2618mm/s, the average friction coefficient decreases from 0.135 to 0.049. As the velocity rises from 2618mm/s to 5236mm/s, the average friction coefficient increases slowly form 0.049 to 0.075.

Fig. 7a shows the test results of COF under different loads and Fig. 7b presents the average friction coefficient of paper-based friction pairs. It can be observed that the effects of load on the COF of paper-based friction material are obvious. As the load rises from 0.7MPa to 2.8MPa, the average friction coefficient increases gradually from 0.098 to

0.124. And the average friction coefficient decreases slightly to 0.117 when the load rises to 3.5MPa. Further, when the load rises to 4.2MPa, the average friction coefficient decreases sharply to 0.058.

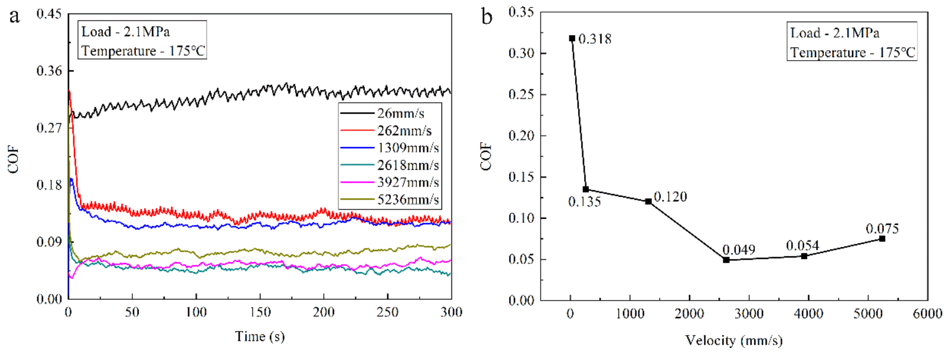

Fig. 6: Test results of COF under different velocities: (a) COF curve; (b) average friction coefficient.

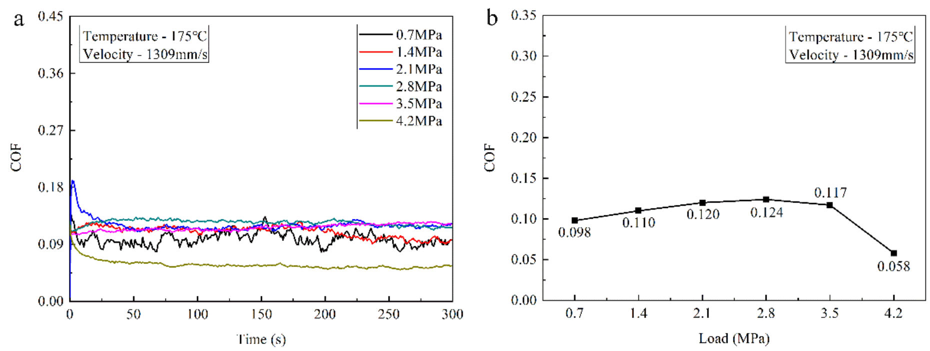

Fig. 7: Test results of COF under different loads: (a) COF curve; (b) average friction coefficient.

Fig. 8a shows the test results of COF under different temperatures and Fig. 8b presents the average friction coefficient of paper-based friction pairs. It is clear that the change of temperature has a significant influence on the COF of paper-based friction material. As the temperature rises from 25℃ to 175℃, the average friction coefficient decreases sharply from 0.266 to 0.120. And the average friction coefficient increases to 0.145 when the temperature rises to 250℃. And the average friction coefficient is nearly the same when the temperature rises from 250℃ to 325℃. But the average friction coefficient decreases sharply to 0.025 when the temperature is 400℃, which means that the paper-based friction material nearly fails.

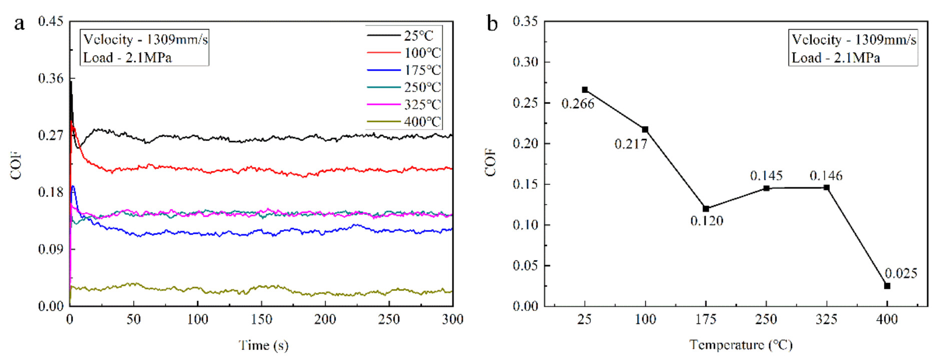

Fig. 8: Test results of COF under different temperatures: (a) COF curve; (b) average friction coefficient.

The analysis above shows that the COF of paper-based friction material decreases to a low level when the velocity, load, or temperature is high, meaning that the material nearly fails. Therefore, the friction performance of the paper-based friction material is dramatically influenced by working conditions. And the average friction coefficient under different dry working conditions can be used in the numerical simulation of wet clutch engagement process in the SAE#2 tests.

3.2. Fluctuation of COF

It can be seen that the curve of COF has fluctuation in all test conditions. The fluctuation of COF means the vibration of friction torque. Therefore, the fluctuation of COF affects the stability of the transmission system and the riding comfort of vehicle. In order to describe and compare the fluctuation of COF, the coefficient of variation of COF curve was calculated. The coefficient of variation (Cv) is calculated by the following equation.

$$C_v = \sigma / \mu \tag{2}$$

Fig. 9a-c respectively show the calculation results of Cv of COF curve against velocity, load, and temperature of the paper-based friction material and the Cv of COF is basically around 0.1. In Fig. 9a, the Cv of paper-based friction material is very low when the velocity is 26mm/s, because of the respectively high mean value of COF. And the Cv is extremely high when the velocity is 262mm/s and 5236mm/s. In Fig. 9b, The Cv of paper-based friction material is particularly low when the load is 2.8MPa and 3.5MPa, but high when the load is 4.2MPa. In Fig. 9c, The Cv of paper-based friction material is very low when the temperature is 250℃ and 325℃. But the Cv is extremely high when the temperature is 400℃. It can be observed that the fluctuation of COF is very high when the operating condition is severe.

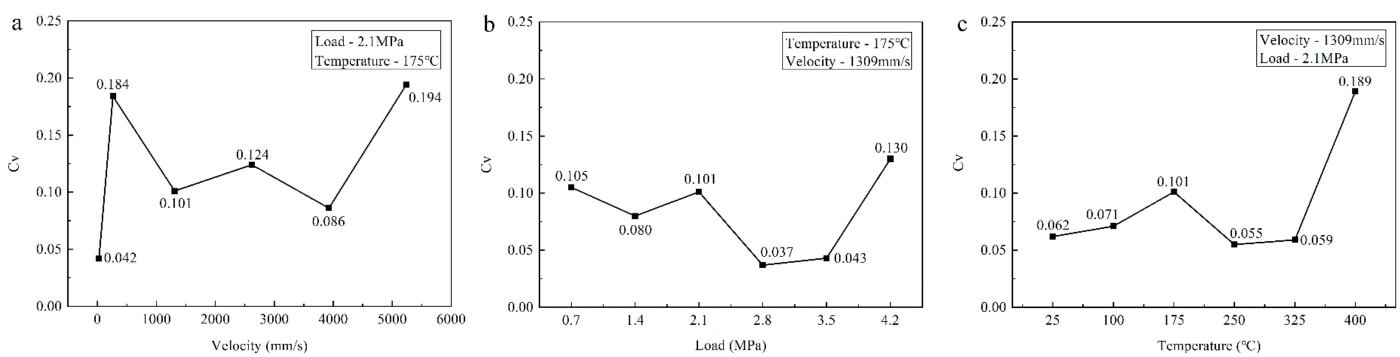

Fig. 9: Coefficient of variation of COF: (a) vs. velocity; (b) vs. load; (c) vs. temperature.

3.3. Wear Mechanism

Fig. 10a-f provides the SEM micrographs of worn surfaces of paper-based friction material after test under different temperatures. More binder has been brought out on the worn surface and the tiny bright stripes are the worn fibers. Further, the smooth bright spots on the worn surface are the friction film. The wear and failure mechanisms of paper-based friction material can be obtained by the conjoint analysis of friction film on worn surfaces and the friction coefficient.

As the temperature rises from 25℃ to 175℃, the softening of friction material gradually takes place because of the setting temperature and sliding heat. As a result, the tangential force produced by asperity shear decreases. It can be observed that the scratches on the friction surface become more and more unapparent in Fig. 10a-c. The contact area between the pin and friction disc becomes increasingly smooth, and the area of friction film increases. Therefore, the COF decreases from 0.266 to 0.120 as the temperature rises from 25℃ to 175℃.

When the temperature rises to 250℃, the thermal degradation of friction material develops further. Some fibers and resin begin to carbonize, leading to an increase of surface roughness and asperity shear, and the slight decrease of friction film area (Fig. 10d). Thus, the COF slightly increases to 0.145. When the temperature rises to 325°C, the fibers and resin further carbonize and slightly oxidize, leading to the severe wear of friction material surface (Fig. 10e). But the COF remains at 0.146.

When the temperature rises to 400°C, the thermal degradation of the paper-based friction material becomes more serious, and the fibers and resin further carbonize and oxidize into volatile elements. As products of the oxidation of fibers and resin, the liquid and gaseous volatile elements act as a lubricant in the friction interface. Thus, asperity shear sharply decreases, and friction film area dramatically increases (Fig. 10f). Therefore, the COF sharply decreases to 0.025.

Therefore, as the rise of operating temperature and the enhancement of heat flux inputting into the friction interface, the thermal degradation, including softening, carbonization, and oxidation of fibers and resin, gradually takes place, changing the friction characteristics and wear mechanism of paper-based friction material. It is observed that the severe wear happened at 325°C and 400°C pin-on-disc tests is similar to the wear phenomenon in Fig. 2b. Therefore, we can confirm that dry friction happened in the middle radius area of the second friction disc in SAE#2 tests under severe operating conditions.

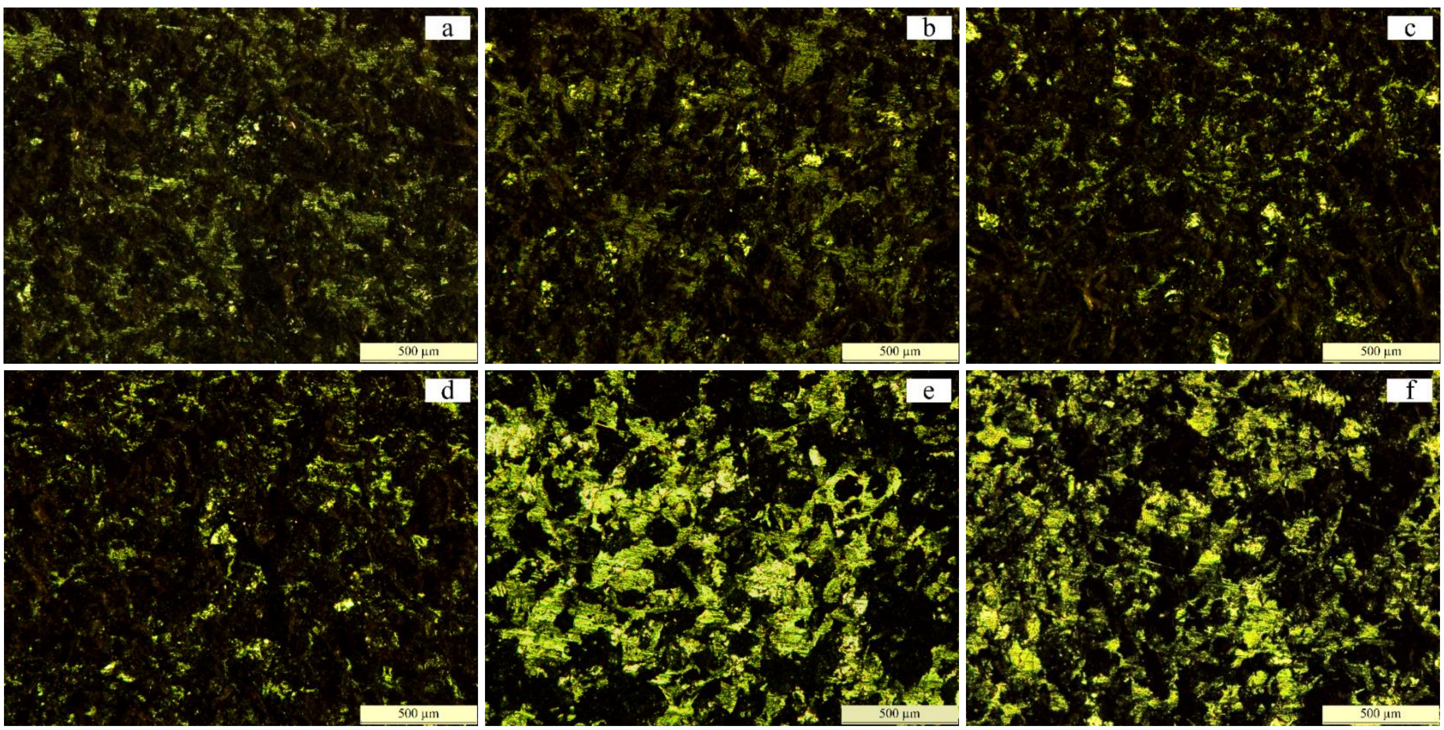

Fig. 10: SEM micrographs of worn surfaces of paper-based friction material after tests: (a) 25°C; (b) 100°C; (c) 175°C; (d) 250°C; (e) 325°C; (f) 400°C.

4. Conclusion

The friction behaviors and wear mechanism of paper-based friction material have been analyzed in this study by pin-on-disc tests. The following conclusions are summarized after the completion of this study:

1. The COF decreases to a very low level in severe working conditions especially in high temperature, which means the failure of friction material.
2. The Cv of COF is basically around 0.1, and it can be observed that the fluctuation of COF is very high when the operating condition is severe.
3. As the rise of operating temperature and the enhancement of heat flux inputting into the friction interface, the thermal degradation of the material, including softening, carbonization, and oxidation of fibers and resin, gradually takes place, leading to the change of COF and wear mechanism.

4. The similar wear phenomenon in high temperature pin-on-disc tests and SAE#2 tests indicates that dry friction happened in the SAE#2 tests under severe operating conditions.

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