Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2015, Article ID 867549, 7 pages
http://dx.doi.org/10.1155/2015/867549

Research Article

Frictional Performance and Temperature Rise of a Mining Nonasbestos Brake Material during Emergency Braking

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Received 16 January 2015; Revised 17 April 2015; Accepted 17 April 2015

Academic Editor: Anna Richelli

By simulating emergency braking conditions of mine hoisters, tribological experiments of a mining nonasbestos brake material sliding on E355CC steel friction disc investigated a pad-on-disc friction tester. It is shown that, under combined influence of braking velocity and pressure, the lubricating film and micro-convex-apices on wear surface would have complex physicochemical reactions which make the instant friction coefficient rise gradually while the instant surface temperature rises first and then falls. With the antifriction effect from lubricating film and the desquamating of composite materials, the mean friction coefficient decreases first, then rises, and decreases again with the increasing of initial braking velocity. And with the existence of micro-convex-apices and variation from increment ratio of load and actual contacting area, it rises first and then falls with the increasing of braking pressure. However, the mean surface temperature rises obviously with the increasing of both initial braking velocity and braking pressure for growth of transformed kinetic energy. It is considered that the friction coefficient cannot be considered as a constant when designing brake devices for mine hoisters. And special attention should be paid to the serious influence of surface temperature on tribological performance of brake material during emergency braking.

1. Introduction

Presently, when designing brake device for a mine hoister, the friction coefficient of its brake shoe was often considered as a constant [1]. But, in fact, the friction coefficient is affected by many factors under actual working conditions, such as velocity, pressure, and temperature [2–5]. In particular, during an emergency braking of mine hoister, because of the heavy load and high velocity, a great deal of friction heat is generated on the surface of the brake shoe. For short time of braking, the friction heat cannot be transferred timely, so the surface temperature rises quickly. The nonasbestos polymer matrix composite material, which is mainly composed of resin binder, nonasbestos fibers, and mining fleur, is widely used as the material of brake shoe for braking of mine hoister nowadays. The high temperature during emergency braking will cause the degradation of the organic binder and the material pyrolysis [6–8]. Therefore, the friction coefficient falls quickly and the braking torque decreases accordingly, which as a result induces serious accidents.

In the past, few studies were focused on the tribological performance of mine hoister's brake shoe. Shi et al. [9] and Zhu et al. [10] investigated the tribological performance of the asbestos and nonasbestos brake shoe of mine hoister, respectively. But their experiments were conducted under a certain sliding velocity, which is different with the changing sliding velocity during emergency braking. By contrast, more investigations were focused on the braking materials of automobiles [11, 12], trains, and airplanes. For example, Gao et al. [13] investigated the tribological performance of carbon fiber reinforced friction material and Kumar et al. [14] investigated brake lining containing metallic fillers for automobiles, respectively. Liang et al. [15] studied the frictional characteristics of four kinds of brake materials used

Table 1: Composition weights of the WSM-3 nonasbestos brake shoe.

Composition	Weight (%)
Phenolic resin modified by Chemigum	12
Chemigum	5
Aramid fiber	4
Fiberglass	17
Graphite	4
Feldspar powder	12
Aedelforsite	20
Frictional powder	4
Barium sulfate	20
Sepiolite	10

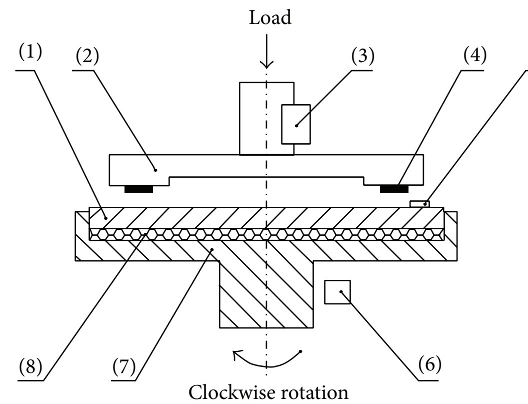
Table 2: Main mechanical properties of the WSM-3 nonasbestos brake shoe.

Properties	Standard	Test
Impact strength (N·cm/cm^2)	>30.38	70
Brinell hardness (N/mm^2)	<490.5	287.8
Water absorption (%)	<1%	0.25%
Oil absorption (%)	<1%	0.19%

in trains; Ozsarac et al. [16] and Gyimah et al. [17] investigated the tribological performance of the carbon-carbon composite brake pads and copper-based powder metallurgy brake materials for railway carriage, respectively. Zhang et al. [18], Xiao et al. [19], and Su [20] investigated the tribological performance of C/C brake shoe composites used in airplanes. The results they had achieved may be quite valuable for automobiles, trains, and airplanes. But the brake materials they had researched are quite different with the nonasbestos brake shoe for mine hoisters, and the working conditions they had simulated in experiments are also different. So, in order to improve the braking ability and reliability of mine hoisters, it is necessary to investigate the tribological performance of their brake shoe during emergency braking. As the friction coefficient is the most important tribological parameter of brake shoe and is seriously affected by the surface temperature, so in this paper the influences of the braking conditions on the friction coefficient and surface temperature were investigated specially.

2. Experiments

2.1. Experimental Materials. A new invented mine brake material called WSM-3 nonasbestos brake shoe for mine hoisters was selected as the experimental material. Its pairing friction disc was made of E355CC (ISO) steel which is a sort of special steel for making brake discs of mine hoisters in China. The basic material of the WSM-3 nonasbestos brake shoe is perbunan modified phenolic resin. The reinforcing materials are kevlar and glass fibers. Some graphite is added as lubricant. Proper mining fleur such as feldspar powder, wollastonite, and barium sulfate are added as tribological regulators [21]. And their composition weights were shown in Table 1.



(1) Friction disc (2) Friction bench (3) Torque sensor (4) Brake shoe (5) Thermocouple (6) Counter sensor (7) Rotation disc (8) Heating pipe

Figure 1: Schematic of the X-DM friction tester.

According to the national standard JB/T 3721-1999 "Brake shoe for disc brake of mine hoister" [22], the main mechanical properties of the WSM-3 nonasbestos brake shoe were tested. And the results are contrasted with the standard in Table 2. It is found that the main mechanical properties of the brake shoe are all better than the technical requirements of the national standard.

2.2. Experimental Apparatus and Method. As it is known, the contacting modality between the brake shoe and disc is surface contact of block and disc, and the motion between them is absolute sliding. Detailedly, the radius of disc is 200 mm and sliding radius is 150 mm. And its thickness is 19 mm. In addition, the length of square pad is between 24.8 mm and 25.0 mm. The X-DM friction tester can preferably simulate the operating conditions of disc brakes for carrying out tribological experiments on it. Its testing principles are in accordance with the national standard JB/T 3721-1999 "Brake shoe for disc brake of mine hoister" [22]. The schematic diagram of its mechanical structure and friction contact is shown in Figure 1.

The testing method of the X-DM friction tester can be expressed as follows. The friction disc rotates towards clockwise direction by the driving of an adjustable speed motor. The revolutions of the motor can be measured by a counter sensor, which is placed nearby the axis of the motor. The positive pressure is loaded onto two pieces of brake shoe samples by a cylinder. The friction torque M is measured by a torque sensor which is fixed on the friction bench. And the friction coefficient μ can be calculated automatically by the computer according to the following formula:

$$\mu = \frac{M}{pAl}, \quad (1)$$

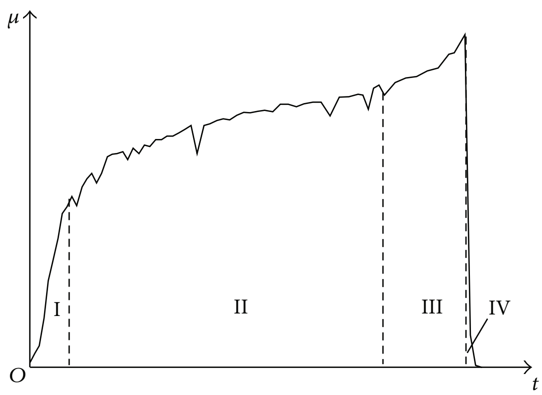


FIGURE 2: Typical curve of the instant friction coefficient during emergency braking.

where M is the friction torque between the brake shoe and disc, N·m; p is the specific pressure of braking, MPa; A is the nominal surface area of the brake shoe, mm^2; l is the arm of friction force, m.

As the brake shoe contacts tightly with the friction disc during the braking process, it is difficult to measure its surface temperature directly. Therefore, on the tester the surface temperature of the brake shoe was indirectly measured by a thermocouple which is placed on the friction disc nearby the friction contacting region.

3. Results and Discussion

3.1. Variations of Friction Coefficient with Braking Conditions

3.1.1. Variation of Instant Friction Coefficient during Emergency Braking. As it is known, the emergency braking is a sliding motion with constant pressure and decelerating velocity. The typical curve of the instant friction coefficient recorded by the tester during an emergency braking test is shown in Figure 2. It is found that the variations of the friction coefficient can be divided into four periods: fast climbing period (I), slow rising period (II), terminal warping period (III), and quick falling period (IV). The quick climbing of friction coefficient at the period (I) reflects the process that the brake shoe is contacting onto the friction disc when the friction bench is dropped. And the reason for the quick falling of friction coefficient at period (IV) is that the brake shoe is uplifting away from the friction disc. As these two periods just reflect the beginning and finishing operations of a braking test, they should not be considered as normal tribological behaviors of the brake shoe, while periods (II) and (III) reflect truly the variations of friction coefficient during an emergency braking, which were then considered for calculating the mean friction coefficient of each braking test.

3.1.2. Variations of Mean Friction Coefficient with Initial Braking Velocity. During the experiments, the testing values of braking pressure are 0.98 MPa, 1.18 MPa, 1.38 MPa, and 1.58 MPa, and the testing values of initial braking velocity are 7.5 m/s, 10 m/s, 12.5 m/s, 15 m/s, and 20 m/s. After crossing of these parameters, there are totally twenty groups of experiments. Three tests were contained in each group for eliminating errors and a virgin pad was applied in every test. By taking the mean friction coefficient of each group of experimental results, the curves in which the mean friction coefficient varies with the initial braking velocity were plotted, shown in Figure 3.

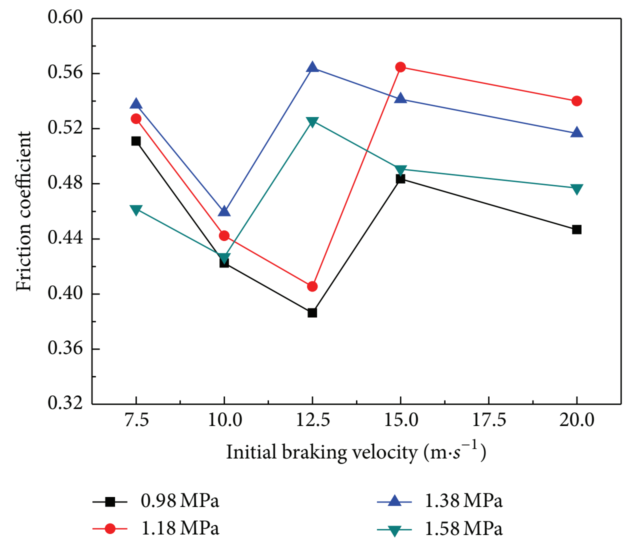


FIGURE 3: Variations of the mean friction coefficient with initial braking velocity.

It is shown in Figure 3 that when the braking pressure is certain, the mean friction coefficient falls first, then rises, and falls again with the increasing of initial braking velocity. When the braking pressure is not higher than 1.18 MPa, the initial braking velocities at the turning point where the friction coefficient turns from falling to rising and from rising to falling are 12.5 m/s and 15 m/s, respectively. However, when the braking pressure is higher than 1.18 MPa, the corresponding velocity at the turning points moves forward to 10 m/s and 12.5 m/s, respectively.

As it is known, the kinetic energy of the disc, which increases quadratically with the initial braking velocity, is mainly transferred into friction heat during emergency braking. When the initial braking velocity is low, the heat caused by friction is not high. But it may be high enough for melting the surface layer material of the brake shoe to form thin lubricating film on the surface. The film has smaller friction coefficient than the base material, which then causes antifriction effect on the surface [23]. Gradually, with the initial braking velocity increasing, the surface of the brake shoe will be fully covered with the lubricous film as shown in Figure 4.

So, in Figure 3, the mean friction coefficient shows falling trend with the increasing of velocity at first. But when the velocity increases higher, the film begins to abrade and desquamate as shown in Figure 5. The antifriction effect it

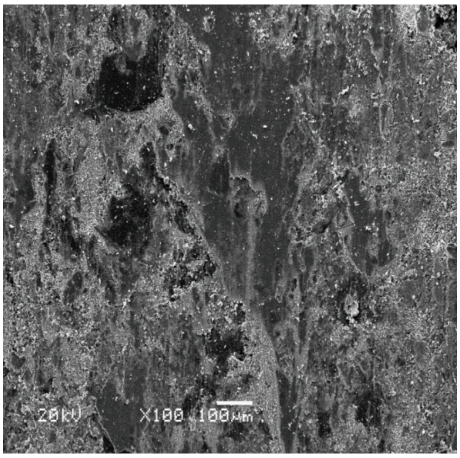


FIGURE 4: SEM picture of surface fully covered with the lubricating film.

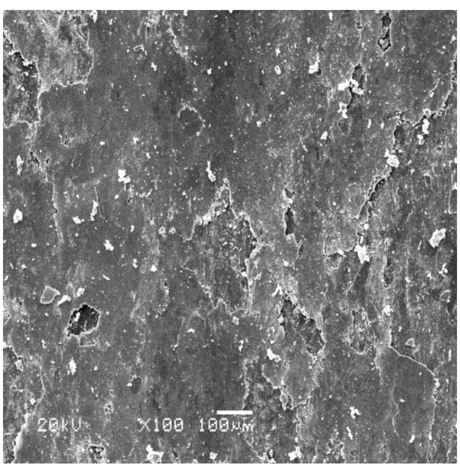


FIGURE 5: SEM picture of the desquamating lubricous film.

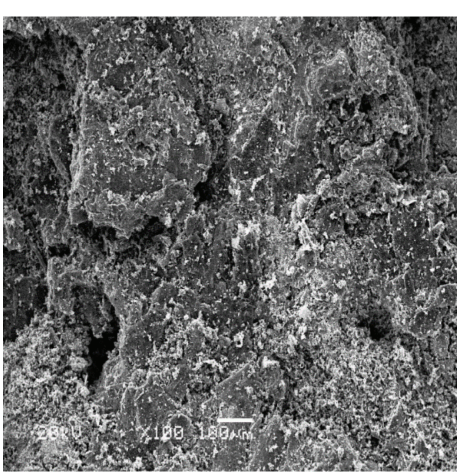


FIGURE 6: SEM picture of the destroyed lubricous film.

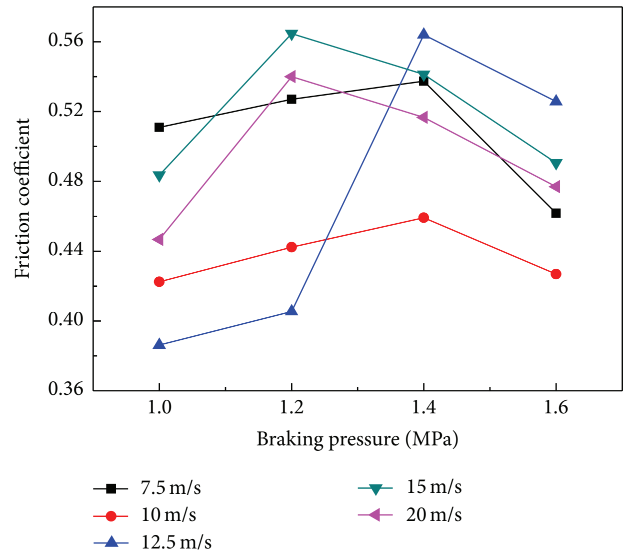


FIGURE 7: Variations of the mean friction coefficient with braking pressure.

caused is then weakened, so the friction coefficient begins to rise.

With the continuous increasing of the initial braking velocity, the film is gradually destroyed as shown in Figure 6. And the base material contacts directly with the disc. Under the actions of high speed and temperature, the resin based bond of the composite friction material cannot polymerize tightly the reinforcing fiber and mining fleur on its surface any more. And they desquamate gradually from the surface with the sliding actions. The actual contacting area is then diminishing, which causes the falling of the friction coefficient.

In Figure 3, the velocity at the point where the friction coefficient turns has a higher value when the braking pressure is lower. This is because when the braking pressure is low, the load acting on the brake shoe is light, so the forming and destroying of the lubricous film all need a higher velocity to supply enough energy.

3.1.3. Variations of Mean Friction Coefficient with Braking Pressure. The curves in which the mean friction coefficient varies with the braking pressure are shown in Figure 7. It can be found from Figure 7 that when the initial braking velocity is certain, the mean friction coefficient rises first and then falls with the increasing of braking pressure. When the initial braking velocity is below 12.5 m/s, the braking pressure at the turning point where the friction coefficient turns from rising to falling is 1.38 MPa. However, when the initial braking velocity increases beyond 12.5 m/s, the turning point moves forward to 1.18 MPa.

Assume that the actual contacting area between the brake shoe and friction disc is A_0 and the shear stress on the brake shoe is τ; then the friction force F can be expressed as follows [2]:

$$F = A_0 \tau. \tag{2}$$

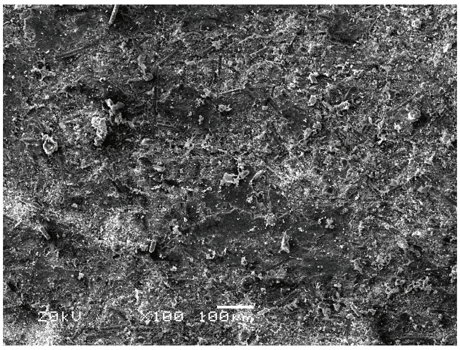


Figure 8: SEM picture of the surface containing micro-convex-apices.

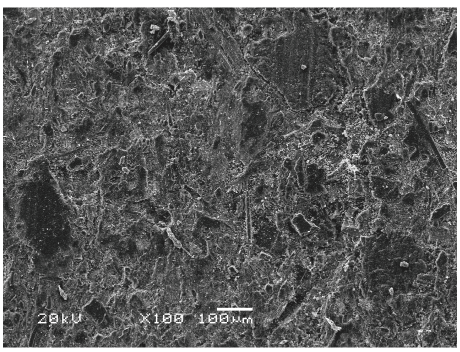


Figure 9: SEM picture of the staved micro-convex-apices.

By combining formula (2) with formula (1), the friction coefficient μ can be calculated as follows:

$$\mu = \frac{A_0 \tau}{pA}. \quad (3)$$

Since the shear stress τ is inherence of material, it is easily found from formula (3) that the friction coefficient μ is direct ratio of the actual contacting area A_0 and inverse ratio of the braking pressure p. When the braking pressure p increases, on the one hand, the denominator of formula (3) also increases, so the friction coefficient will decrease. But, on the other hand, as the increasing of load makes the actual contacting area A_0 bigger, the friction coefficient may increase, too. In fact, if the increasing of braking pressure causes a bigger increment ratio of the actual contacting area, then the friction coefficient will rise. On the contrary, if the increment ratio of the contacting area is smaller than the load, then the friction coefficient will fall.

When the braking pressure is low, there are still many micro-convex-apices distributed on the surface of the brake shoe as shown in Figure 8. With the increasing of the braking pressure, these micro-convex-apices are easily staved to add actual contacting area as shown in Figure 9, which then causes an increment of friction coefficient in Figure 7 at the low pressure period. When the braking pressure is high, the contact between the brake shoe and friction disc may have been sufficient.

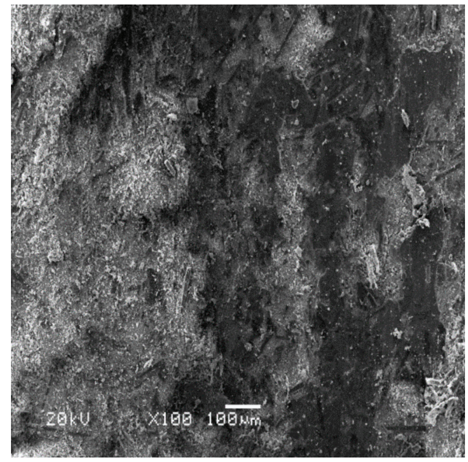


Figure 10: SEM picture of the actual contacting area under limit state.

So the increment of the actual contacting area is quite limited when the braking pressure is increasing as shown in Figure 10. The increment ratio of the load may be bigger than that of the actual contacting area, which as a result causes a decrement of friction coefficient at the high pressure period.

In Figure 7, the braking pressure at the point where the friction coefficient turns has a bigger value under a lower initial braking velocity. This is because when the initial braking velocity is lower, the wearing distance during the same period is shorter. So it needs a bigger pressure to make the actual contacting area increase.

3.2. Variations of Surface Temperature with Braking Conditions

3.2.1. Variation of Instant Surface Temperature during Emergency Braking. The typical curve of the instant surface temperature which was recorded by the tester during a braking test is shown in Figure 11. It can be found that the surface temperature rises first and then falls after reaching the highest temperature during the braking process.

Based on the energy conversion thoughts, the emergency braking of mine hoister is a process of exhausting kinetic energy by transferring it into heat energy. Since the emergency braking aims at stopping the hoister as soon as possible, in the short time, a great deal of friction heat is generated for high speed sliding. Some of the heat energy is transferred into the environment by heat conduction and convection. And the rest of heat is mostly absorbed by the brake shoe and friction disc, which makes their surface temperature rise quickly. At the beginning period of braking, the sliding velocity between the brake shoe and friction disc is very high. And the absorbed heat caused by the sliding friction is much higher than the heat transferred into environment. So, in Figure 11, the surface temperature rises obviously at first. With the braking process continuing, the sliding velocity falls gradually. And the surface temperature arrives at the highest value when the friction heat generated has decreased to balance with the heat transferred. Subsequently,

Figure 11: Typical curve of the instant surface temperature during emergency braking.

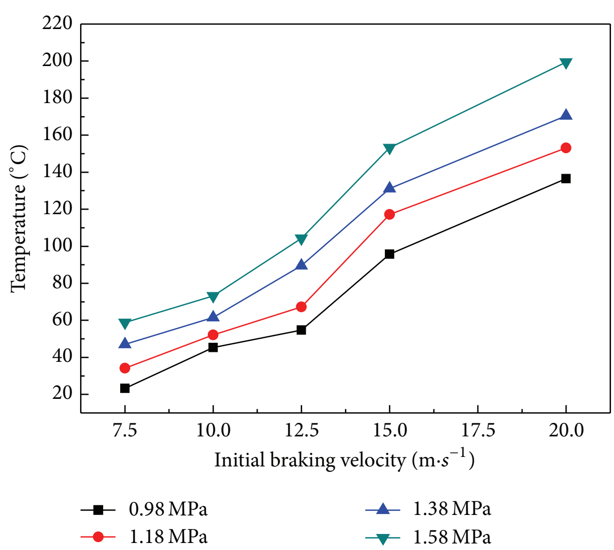


Figure 12: Variations of the mean surface temperature with braking conditions.

at the final braking period, the heat caused by friction is obviously weakened with the sliding velocity falling. The heat absorbed is smaller than the heat transferred, so the surface temperature begins to fall gradually.

3.2.2. Variation of Mean Surface Temperature with Braking Conditions. By taking the mean values of each braking test, the curves of the mean surface temperature varying with the initial braking velocity and braking pressure were plotted, shown in Figure 12. It is found that the mean surface temperature rises obviously with the increasing of both initial braking velocity and braking pressure.

As it is known, the emergency braking transforms kinetic energy into friction heat, and the kinetic energy is quadratic of initial braking velocity. So it is easy to understand that in Figure 12 the surface temperature rises obviously with the increasing of initial braking velocity. And when the initial velocity is certain, a higher braking pressure causes a heavier friction force and makes a bigger frictional power in the same wearing distance. The friction heat transformed by the braking is more, so the surface temperature is higher. On the other hand, a higher braking pressure makes a bigger braking force moment and a shorter braking time. Less heat can be transferred into the environment, which may also cause a higher surface temperature.

4. Conclusions

In this paper, by the simulating of emergency braking conditions of mine hoister, some tribological experiments of its nonasbestos brake shoe were conducted. And the influences of the braking conditions on the friction coefficient and surface temperature were discussed. Based on these works, some conclusions were achieved as follows.

(1) Under combined influence of initial braking velocity and pressure, lubricating film and micro-convex-apices on the wear surface would have complex physicochemical reactions; this would make instant friction coefficient of the brake shoe show a continuous climbing trend during emergency braking, while the instant surface temperature rises first and then falls after reaching the highest value, which depends on balance relationship between the absorbed and transferred heat.

(2) As the antifriction effect from lubricating film and the desquamating of composite materials, the mean friction coefficient of the brake shoe falls first, then rises, and falls again with the increasing of the initial braking velocity when the braking pressure is certain. And for the need of enough energy, the initial braking velocity at the turning point of friction coefficient has a higher value when the braking pressure is lower.

(3) With the existence of micro-convex-apices and variation from increment ratio of load and actual contacting area, the mean friction coefficient of the brake shoe rises first and then falls with the increasing of the braking pressure when the initial braking velocity is certain. And for the absence of actual contacting area, the braking pressure at the turning point of friction coefficient has a bigger value under a lower initial braking velocity.

(4) The mean surface temperature of the brake shoe rises obviously with the increasing of both initial braking velocity and braking pressure, which mainly derives from growth of transformed kinetic energy in the same time.

(5) As the friction coefficient of the brake shoe varies continuously with the braking conditions, it cannot be considered as constant when designing braking devices for mine hoisters. Special attention should be paid to the tight connections of surface temperature with braking conditions during emergency braking. And the influence of the surface temperature on the

tribological performance of brake shoe should be further investigated in the future.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This study was financially supported by the Natural Science Funds of China (Grant no. 51205395), the Open Funds of State Key Laboratory of Solid Lubrication (Grant no. LSL-1204), the Six Major Talent Peak Projects of Jiangsu Province (Grant no. 2011-ZBZZ041), and the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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