A Study on the Tribological Behavior of Polyethylene. II. Effects of Operating Conditions on the Friction Behavior of Polyethylene

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SYNOPSIS

In this article, the effects of the operating conditions, i.e., load, oscillation speed, temperature, and contact modes on the friction behavior of polyethylene were studied through the SRV vibration friction test machine, the MHK-500 friction and wear test machine, as well as an on-line temperature testing device. The experimental results showed that the friction coefficient μ of polyethylene increases with increase of the oscillation frequency and amplitude, the speed, and PV value, while load has a quite complex impact on μ; suitable choice of load could reduce μ and smoothen the friction process. Contact modes of friction pairs have considerable effects on μ, because all the real contact area of the friction assembly, the pressure, the indentation of surface asperities, as well as the temperature rise and distribution in the contact region are related to contact modes. Temperature is a key factor determining the viscoelastic properties of polyethylene, and therefore has great effect on μ. On-line temperature testing offers a way to reveal the relations between temperature and the friction behavior of polyethylene. All the results obtained provide the basic data for establishing mathematical models and computational simulation methods to describe and study the tribological behavior of some polymer materials.

INTRODUCTION

The economic losses due to friction and wear of materials are very high. For example, in China alone it reaches up to 4×10^{11} RMB yuan per year. It is of both scientific and commercial interest to develop new materials with low friction coefficient and high wear resistance.

Owing to their excellent tribological properties, such as low friction, high wear resistance, ease of running-in, absorption of impact and vibration, anticorrosion, and self-lubrication, polymeric materials are widely used in industries. On the other hand, the dependence of tribological behavior of friction assemblies on material properties and operating conditions is much stronger for polymeric materials than for metals. Therefore one of the most important factors for developing polymeric materials with low friction and high wear resistance is to correctly describe the dynamic contact process and investigate the effects of material features and operating conditions on their tribological behavior. For this purpose, we have systematically studied the tribological behavior of polyethylene/stainless steel assembly. As mentioned in the first part of this study,[1] the choice of polyethylene is based on the following considerations:

- Polyethylene is one of the common plastics with large production and wide applications. It is expected to become engineering plastics by means of blending and compositing. For example, high-density polyethylene (HDPE), because of its regular molecular structure, has excellent friction property and has been widely used in the field of tribology.
- Polyethylene-based materials have a wide structure-property spectrum. Although poly-

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ethylene is a polymer with the simplest monomeric unit ethylene, by means of different polymerizations, or by copolymerizing ethylene with various α-olefins, or by blending and composting, it can be tailored to have different structures and properties, and it is therefore suitable for studying the effect of material features on the friction and wear of polymeric materials.

- The melting point of polyethylene materials is not very high. Their tribology behavior strongly depends on the operating conditions. This makes polyethylene suitable also for studying the effects of operating conditions on the tribological behavior of materials. In addition, polyethylene materials have good process ability, and low price.

In our preceding article,[1] seven kinds of polyethylene materials were studied to evaluate the influence of material features, such as the length of side chain, surface hardness, yield strength, and surface roughness, on the coefficient of friction. The experimental results showed that homopolymerized high-density polyethylene 2100J has the lowest coefficient of friction, and the reason is that it has a regular molecular structure, and a higher degree of crystallization, density, hardness, and strength.

In this study, focusing on the friction coefficient of PE2100J/stainless steel assembly under different operating conditions, we investigate the effects of load, oscillation frequency and amplitude, speed, PV value, contact modes, as well as temperature on the tribology behavior of the contact system.

EXPERIMENTAL

Material

HDPE, 2100J, $\bar{M}_\eta = 7.26 \times 10^4$, $\rho = 0.959$ g/cm^3, degree of crystallization: 66.8%.

Sample Preparation

The samples for the friction test were prepared by press molding under certain temperature and pressure, then by conversion into disks of $\phi = 24 \times 7.8$ mm (for sliding friction test) or by machine cutting into slices of $18 \times 11.7 \times 4$ mm (for rolling friction test). The surfaces of the samples were polished on abrasive papers. For the rolling friction test samples, copper wires were embedded beneath the sample surface, which can be connected to thermal couples. In this way, the temperature variation during friction can be detected on-line.

Measurement

The coefficient of sliding friction of polyethylene/stainless steel assembly under different operating conditions was measured on the SRV test machine (made by Optimal Co., Germany) for vibration friction. The rolling friction coefficient under different loads and speed was measured on the MHK-500 friction and wear machine (made by Jinan Material Co., China). The thermal couples were welded onto copper wires embedded beneath sample surfaces, thus the voltage changes due to rising temperature could be detected by a voltmeter. Through temperature–voltage calibration, the temperature changes in the dynamic contact area during friction can be more precisely recorded.

The scar widths of the worn samples were measured with a microscope.

RESULTS AND DISCUSSION

Effects of Operating Conditions on the Sliding Friction Coefficient of Polyethylene

Load

Figure 1 demonstrates that load has complex impact on the sliding friction coefficient of PE2100J/stainless steel assembly. Under low load, the friction coefficient μ decreases with increase of load. After passing through a valley, μ increases with increases of load. When load reaches a certain value, μ starts to decrease again. This is a common phenomenon observed for the relationship between the load and the

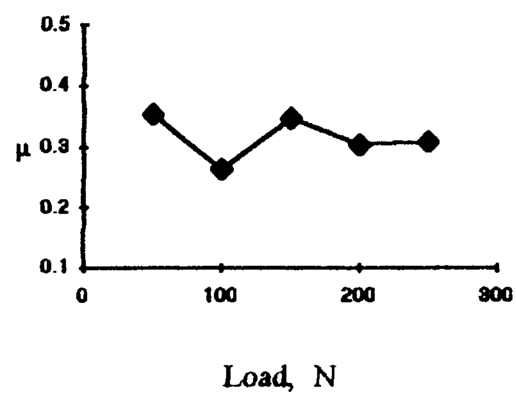

Figure 1 Effect of load on friction coefficient μ of PE. Test conditions: PE 2100J; contact method, area–area; temperature, 25°C; frequency, 50 Hz; amplitude, 2.00 mm; time, 2 h.

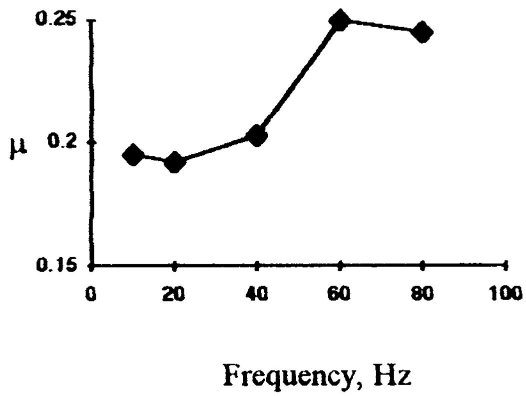

Figure 2 Effect of oscillation frequency on μ of PE. Test conditions: PE 2100J; contact method, area–area; temperature, 25°C; load, 100 N; amplitude, 2.00 mm; time, 2 h.

friction coefficient of polymeric materials, as reported by V. A. Bely et al.[2]

According to the molecular–mechanical theory of friction, friction is a complex process. Among many mechanisms of solid friction, there are two most important procedures: the abrasion of the surface of a softer solid by the surface irregularities of a harder contact counterpart (ploughing), and the cohesive shear in the real contact surface. The friction force F is the sum of the adhesive bonding force F_a and the resistance F_d: $F = F_a + F_d$. The coefficient of kinetic friction can be expressed as[3]:

$$\mu = \mu_a + \mu_d = \frac{\tau_0 A_r}{P} + \beta + K_x\sqrt{\frac{h}{r}} \qquad (1)$$

where τ_0 is the shear resistance needed to break the molecular adhesive bonds, A_r the real contact area, P the normal contact load, β a parameter related to the molecular force of friction, h the indentation of surface aspirates, r the radius of curvature of aspirates, and K_x a parameter related to mechanical force of friction. For area–area contact, the real contact area can be approximately expressed as[4]:

$$A_r = \left(\frac{AP^2 r}{C_3 E^2 R_q}\right)^{1/3} \qquad (2)$$

where A is the nominal contact area, R_q is the mean square deviation, and E is the elastic modulus of material. Substituting eq. (2) into eq. (1), we have:

$$\mu = \tau_0\left(\frac{Ar}{C_3 E^2 R_q P}\right)^{1/3} + \beta + K_x\sqrt{\frac{h}{r}} \qquad (3)$$

Under small load, the contact of PE/stainless steel assembly can be treated as an elastic or viscoelastic one and μ decreases with increase of load. The increase of load may lead to a transition region from viscoelastic contact to viscoplastic contact. In this region μ goes down to its minimum value. As load increases further, the assembly behaves with some viscoplastic contact properties. At this time, μ increases with increase of load, due to the reduction of elastic modulus E and the increase of indentation of surface aspirates h. Under high load, the local melting of materials at contact surface might cause the decrease of friction coefficient μ.

Oscillation Frequency and Amplitude

Figures 2 and 3 show the effect of oscillation frequency and amplitude on the friction coefficient μ of PE2100J/stainless steel assembly. The value of μ increases with increase of oscillation frequency and amplitude, probably because the translated film formed during the dynamic contact of the assembly cannot withstand the repeated friction. As oscillation frequency or amplitude increase, the translated film may be rubbed off or moved out due to material fatigue, and this results in the increase of μ.

Sliding Speed

Sliding speed depends on oscillation frequency and amplitude. Its effect on the friction coefficient μ reflects the comprehensive influences of oscillation frequency and amplitude. Figure 4 shows that μ increases with increase of sliding speed. The increasing rate, however, varies with the speed. At low speed, μ increases slowly. As speed exceeds 0.3 m/s, μ increases rapidly. Again, this may be due to the rubbing off of the translated film that cannot withstand

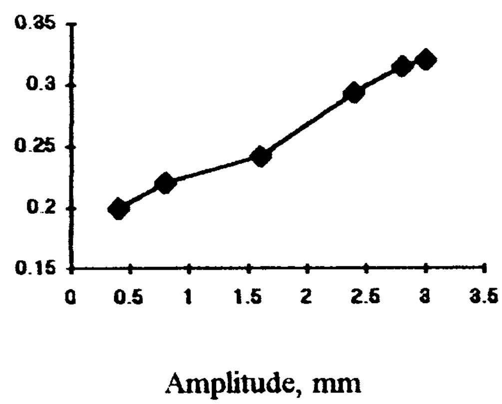

Figure 3 Effect of oscillation amplitude on μ of PE. Test conditions: PE 2100J; contact method, area–area; temperature, 25°C; load, 100 N; frequency, 50 Hz; time, 30 min.

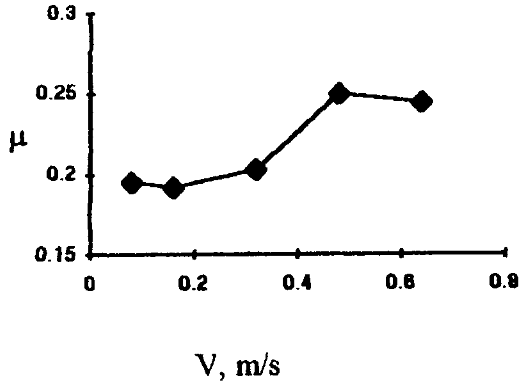

Figure 4 Effect of speed on μ of PE. Test conditions: PE 2100J; contact method, area–area; temperature, 25°C; load, 100 N; amplitude, 2.00 mm; time, 2 h.

repeatedly friction at high speed. On the other hand, the local temperature rise resulting from friction heat may change materials' viscoelasticity or other mechanical properties, leading to the increase of μ. When the sliding speed reaches a certain value, μ tends to decline. This is probably due to the local melting of polymer surface, a direct result of the temperature rise at high speed.

According to the classical law of friction, the friction force is independent of sliding speed between the contact pairs. In fact, however, the friction coefficients of many kinds of contact pairs vary considerably with sliding speed. This phenomenon demands even more consideration for polymeric materials, because of their unique viscoelasticity. However, in studying the effect of speed on the friction coefficient, the main difficulty is to distinguish the effect of speed from the effect of temperature. Although the experiments were carried out under the constant environmental temperature of 25°C, the high temperature rise and the great temperature gradient of polyethylene in the dynamic contact region are not negligible. They result from the friction heat and the poor heat conductivity of polyethylene, and they will certainly exert great impact on the materials' viscoelasticity as well as other mechanical properties. This explains why the sliding speed has a complex effect on the tribological behavior of materials, especially for polymers. In literature,[2] some authors have reported that μ increases with speed, or decreases with speed, or increases with speed at first then decreases with speed afterwards. Our experimental results show that at low speed, speed has little effect on μ (i.e., the classical law of friction is suitable in the low-speed region). At high speed, the stress state as well as the friction heat due to high speed will affect the materials' viscoelasticity. This in turn greatly influences the friction coefficient.

PV Value

The effect of PV value reflects the comprehensive action of load and sliding speed on the friction coefficient. As shown in Figure 5, μ increases with increase of PV value.

Contact Mode

Figure 6 shows the relationship between load and friction coefficient of PE2100J/stainless steel assembly for different contact modes, namely, dot–area, line–area, and area–area. No matter what the contact mode is, the variation of μ with load is similar: with increase of load, μ goes down, passes a valley, then goes up. For dot–area contact, with increase of load, μ decreases very rapidly, and the minimum value of μ appears at low load. After that μ increases rapidly again, and does not decrease thenceforward. For area–area contact, with increase of load, μ decreases slowly, and the minimum value of μ appears at higher load. After that, μ increases again. For line–area contact, the varying degree of μ with increase of load is between the modes of dot–area and area–area, and the minimum value of μ appears at high load. After that μ increases with increase of load, and does not decrease again.

Figure 7 shows the relationship between sliding speed and the friction coefficient of PE2100J/stainless steel assembly for different contact modes. For dot–area contact, μ increases sharply with increase of speed. For line–area contact, at low speed, μ is quite high and slightly changes with speed. When speed exceeds 0.3 m/s, μ increases rapidly with increase of speed. For area–area contact, at low speed, μ is small and fluctuates slightly with speed. When speed exceeds 0.2 m/s, μ in-

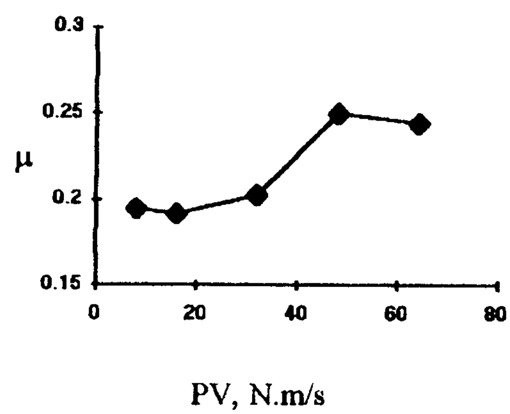

Figure 5 Effect of PV value on μ of PE. Test conditions: PE 2100J; contact method, area–area; temperature, 25°C; frequency, 50 Hz; amplitude, 2.00 mm; time, 2 h.

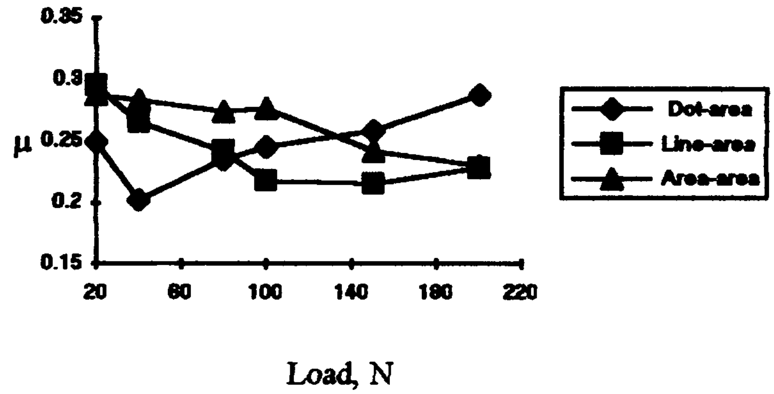

Figure 6 Effects of contact mode and load on μ of PE.

creases with increase of speed. Above the level of 0.6 m/s, μ declines again.

The experimental results mentioned above demonstrate that the contact modes of friction pairs have considerable effects on the friction coefficient of polyethylene. For different contact modes, the real contact area A_r is different. The A_r of area–area is the largest in all contact modes. Under the same load level, the pressure and the indentation of surface asperities, which determine the ratio of F_a to F_d, are different for different contact modes. In addition, the temperature rise and distribution in the contact region are greatly influenced by the choice of contact modes.

Effects of Operating Conditions on the Rolling Friction Coefficient of Polyethylene

On-Line Temperature Test

As stated above, the effect of operating conditions on the friction coefficients of polyethylene reflects the special viscoelasticity of polyethylene. Among other things, temperature is a key factor. For the measurement of sliding friction characteristics, we used the SRV vibration friction test machine, a temperature-controllable friction test device. The controlled temperature is that of the sample rack. During the friction test, however, the temperature at the contact surface is quite different from that of the sample racks, due to the poor heat conductivity of polyethylene. In order to detect the surface temperature of the dynamic contact region more precisely, we designed an on-line temperature-testing device. Copper wires with good heat conductivity were embedded beneath the surface of a polyethylene sample, then welded to a thermal couple. The voltage change due to temperature rise during rolling friction testing could be detected by a voltmeter. By temperature–voltage calibration, the temperature which is more approximate to the actual temperature of dynamic contact area could be measured. In this way, we can investigate the effects of rotational speed and load on temperature rise, and the effect of temperature on the friction coefficient.

Rotational Speed

An important parameter in rolling friction testing of polyethylene/stainless steel assembly is the ro-

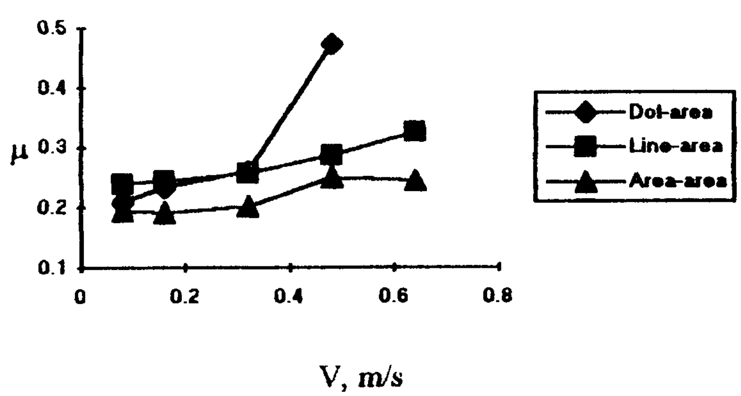

Figure 7 Effects of contact mode and speed on μ of PE.

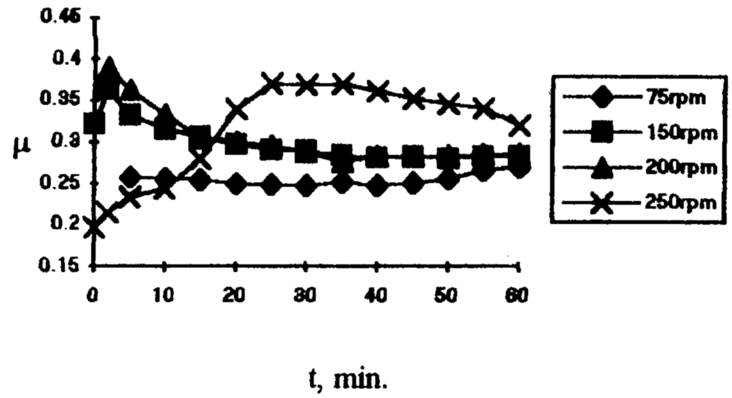

Figure 8 Effect of rotational speed on μ of PE.

tational speed of the steel spinning ring. Figure 8 shows the experimental results of friction coefficients at different rotational speeds under a load of 123.6 N. It is obvious that the rotational speed has a great effect on the friction coefficient. At low speed (75 rpm), the friction process is relatively stable; μ is small and changes with time slightly. As speed increases (150 rpm, 200 rpm), μ increases. At the initial stage of the test, μ increases rapidly and reaches its maximum around 5 min. After that μ decreases, and we have a stable stage. When the rotational speed is as high as 250 rpm, the friction process is unstable, and μ varies considerably. At the beginning of the test, μ is quite small, but increases sharply as time advances. After 30 min, μ declines. Referring to Figure 9, we can further analyze the reason that rotational speed affects μ of polyethylene. This figure shows the surface temperature of polyethylene detected by the on-line temperature-testing device. It can be seen that at low speed, μ is small, and friction heat is unnoticeable. The surface temperature of polyethylene remains around 30°C. After 45 min, temperature increases, responding to the slight increase of μ. When the rotational speed is 150 or 200 rpm, μ is quite high. A large amount of friction heat cannot be transferred promptly, resulting in the rapid increase of temperature at the contact surface. This is the stage of viscoplastic contact and μ increases rapidly. As temperature reaches a certain value, local melting of polyethylene from overheating may lead to the decrease of μ. When the friction heat balances the heat transferred by the assembly, the surface temperature of polyethylene remains constant, responding to the constant μ value at this stage. At high speed (250 rpm), the large amount of friction heat cannot be transferred promptly. Therefore, the temperature rise at the polymer surface is remarkable. The friction process is unstable; μ increases rapidly. The fact that μ varies with the surface temperature of polyethylene confirms that temperature variation is a key factor for the friction coefficient of polymeric materials, such as PE.

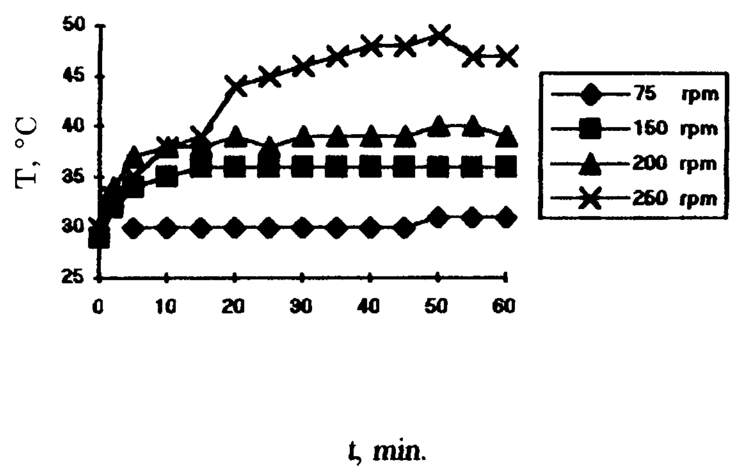

Figure 9 Surface temperature of PE at different speeds and times.

Load

In tribology, the effect of load is one of the most fundamental issues. According to classical friction law, friction coefficient μ is a constant, independent of load. Modern experiments, however, reveal that load determines the real contact area as well as the indentation of surface asperities. Figure 10 shows the experimental values of μ at different load levels, while the rotational speed is kept at 200 rpm. We can see that for polymeric materials the effect of load on μ is quite complicated. Under low (74.6 N) or high (172.7 N) load, the friction process is unstable, and μ varies greatly. Under medium load (123.6 N), however, μ is relatively small, and the process is more stable, probably because the assembly is in the transition region from viscoelastic to viscoplastic (see the valley on the line in Fig. 1). Referring to Figure 11, we can further analyze the reason that load affects the friction coefficient of polyethylene. This figure illustrates the surface temperature variation recorded by the on-line temperature-testing device. The higher the load, the more quickly the temperature rises. As temperature increases, the elastic modulus E and the hardness of the material underneath the contact surface decrease, while the real contact area and the indentation of surface asperities increase, leading to the increase of μ. When temperature rise reaches a certain value, the local melting of polymer from overheating causes μ to decline. When heat transferred by the friction assembly balances the friction heat, the temperature remains stable. Under high load, μ is large, and the great amount of friction heat cannot be transferred quickly. The surface temperature rises rapidly and varies with time. The process is very unstable. The reasons are as follows: High temperature and high load may aggravate the ploughing effect in friction, increase the real contact area, and reduce the materials' hardness and rigidity, resulting in the increase of μ value. On the other hand, high temperature and high load may also cause the local melting or orientation of polymeric materials, resulting in the decrease of μ value. At medium load, surface temperature rise causes polymeric material in the friction pair to be in the transition region from viscoelastic contact to viscoplastic contact. As mentioned above, in this situation, the μ value is the smallest. The temperature change during friction even favors the reduction of μ. It can be drawn from this experiment that the right choice of load can reduce μ, smoothen the friction process, and optimize the assembly operation.

Effect of Rotational Speed and Load on the Wear of Polyethylene Material

Friction leads to wear of materials. The wear process is also very complicated. The material features of friction assembly and the operating conditions all affect wear. In this study, the effect of rotational speed and load on wear of polyethylene materials during rolling friction was investigated with the MHK-500 friction and wear test machine and a microscope. Table I lists the scar widths of polyethylene worn at different speeds and loads. Obviously, the scar width increases with increase of speed. Under lower load, the load slightly affects wear. It should be noticed here that the wear under medium load is less than that under low load, demonstrating that a suitable selection of load could reduce material wear. Under high load, the amount of wear increases considerably. The effects of speed and load also reflect the viscoelasticity of polymeric materials. Friction results mainly from the interface adhesion and energy consumption of surface deformation of materials. High speed and high load produce a large amount of friction heat, leading to surface temperature rise, and influencing the viscoelastic properties

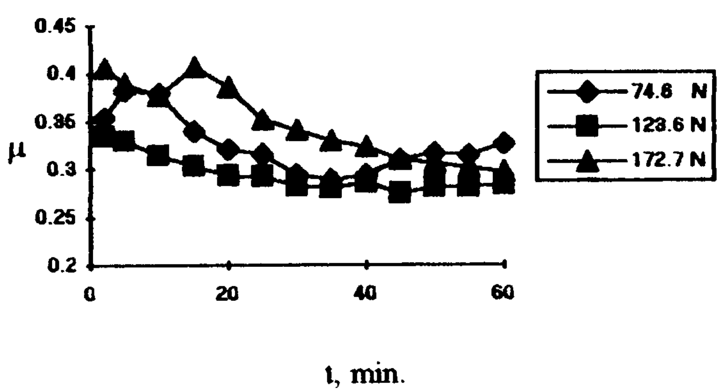

Figure 10 Coefficient of friction of PE at different loads and times.

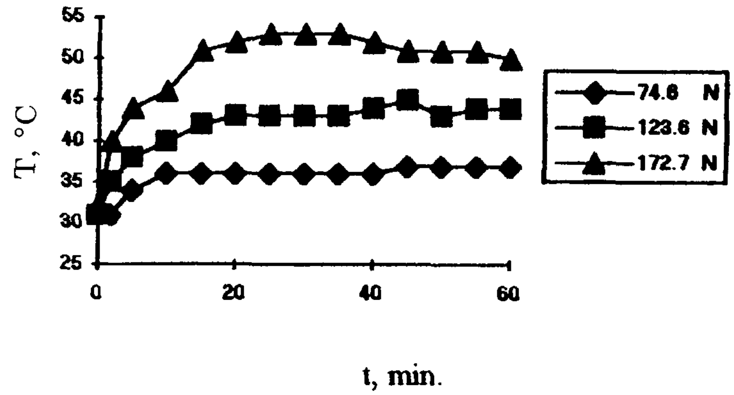

Figure 11 Surface temperature of PE at different loads and times.

and the contact nature of the friction pair. The macroscopic phenomenon is the increase of wear.

CONCLUSIONS

The friction coefficient of polyethylene/stainless steel assembly reflects the comprehensive effects of material features and operating conditions on the tribological behavior of the contact system. HDPE exhibits excellent friction property due to its regular molecular structure. The friction coefficient μ of PE increases with increase of the oscillation frequency and amplitude, speed, and PV value, while load has quite complex impact on μ; suitable choice of load could reduce μ and smoothen the friction process. Contact modes of the friction pairs also affect μ of PE greatly, because all the real contact area of the friction assembly, the pressure, the indentation of surface asperities, as well as the temperature rise and distribution in the contact region are related to contact modes. Temperature is a key factor determining the viscoelastic properties of polyethylene, and therefore has considerable effect on μ. All the experimental results obtained provide the basic data for developing a mathematical model to describe and simulate numerically the tribological behavior of polymer materials.

Table I Effects of Rotational Speed and Load on the Scar Width of Worn PE

Load = 123.6 N		Rotational Speed = 200 rpm	
Rotational Speed (rpm)	Scar Width (mm)	Load (N)	Scar Width (mm)
75	2.74	74.6	2.98
150	3.09	123.6	2.92
200	3.12	172.7	4.12
250	3.19		

t = 60 min.

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REFERENCES

1. Q. Wang, X. Kong, L. Zhu, J. Zhe, and Y. Fan, *Proceedings of the Third National Symposium on Deformation, Damage and Fracture of Polymers,* Chengdu, China, Oct. 1994, p. 269.
2. V. A. Bely, A. I. Sviridenok, M. I. Petrokovets, and V. G. Savkin, *Friction and Wear in Polymer-Based Materials,* Pergamon Press, Oxford, 1982, Chap. 2.
3. Chinese Society of Mechanical Engineering, Ed., *Lubrication Engineering.* Mechanical Engineering Press, Beijing, 1986.
4. W. Dai, *Basic of Tribology,* Shanghai Press of Science & Tech., Shanghai, 1984, Chap. 4.

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