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Materials Science and Engineering A266 (1999) 155–160

MATERIALS SCIENCE & ENGINEERING A

Sliding wear behavior and mechanism of ultra-high molecular weight polyethylene

Y.Q. Wang [a,*], J. Li [b]

[a] *Beijing Laboratory of Electron Microscopy, Institute of Physics and Center for Condensed Matter Physics, Chinese Academy of Sciences, P.O. Box 2724, Beijing 100080, People's Republic of China*

[b] *Department of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, People's Republic of China*

Received 1 October 1998; received in revised form 17 December 1998

Abstract

In this paper, the dry sliding wear behavior of ultra-high molecular weight polyethylene (UHMWPE) was tested on an MM200 rig. The effects of sliding speed and load on the sliding wear of UHMWPE were determined. Scanning electron microscopy (SEM) was employed to examine the worn surfaces. The SEM images showed that a series of ridges were formed on the UHMWPE surfaces in the running-in period and the massive tearing and rupture of the surface layer of UHMWPE occurred in the severe wear period. The thermal effect on the wear of UHMWPE was detected by differential scanning calorimeter (DSC).

Keywords: Ultra-high molecular weight polyethylene; Sliding wear; Wear mechanism

1. Introduction

Many polymers and polymer-based composites are used as bearing components because of their excellent wear resistance. Lots of scholars studied the sliding wear properties and mechanisms of the polymers. In recent years, the study on sliding wear of ultra-high molecular weight polyethylene (UHMWPE) has caused wide interests [1–10]. Atkinson et al. [1] found that there are two periods in the wear of high molecular weight polyethylene (HMWPE): wearing-in period and steady-state period. Marcus et al. [7,8] studied the effect of the fillers on the sliding wear of UHMWPE and sliding behavior of UHMWPE. Cooper et al. [3] distinguished two wear processes of UHMWPE: microscopic wear and macroscopic polymer asperity wear. Wang et al. [9] proposed two theoretical wear models based on the scale of intimate asperity interactions. UHMWPE is a wear-resistant polymer with a moderate coefficient of friction against a steel counterface. The design of bearings and sliding contacts made from UHMWPE or other polymers is usually based on PV limit where P is the apparent contact pressure and V is the sliding speed [5].

The wear of polymers is complex. The friction and wear of polymers involve time-dependent and temperature-dependent properties related to their distinguished properties from metals such as visco-elastic behavior [11]. The influence of tribosystem parameters on wear is even stronger than for metals [11].

Tribologists often classify thermoplastic polymeric materials into three distinct groups according to their friction and wear behavior [12,13]. These are: the 'smooth molecular profile' polymers such as high density polyethylene (HDPE), UHMWPE and polytetrafluorethylene (PTFE); the normal polymers such as low density polyethylene (LDPE) and polypropylene (PP); and the amorphous polymers such as polymethylmethacrylate (PMMA) and polyvinyl chloride (PVC). Among them, the better frictional performance of the smooth molecular profile polymers can be explained by the easiness with which the long chain molecules shear across each other.

In this paper, the relationship between the mass loss, applied load, sliding speed, and sliding distance (the wear time) was studied. The authors explored the wear

* Corresponding author. Tel.: +86-10-6256-8304; fax: +86-10-6256-1442.

E-mail address: yqwang@image.blem.ac.cn (Y.Q. Wang)

0921-5093/99/$ - see front matter
PII: S0921-5093(99)00040-4

mechanism of UHMWPE by using scanning electron microscopy (SEM) to examine the worn surfaces of UHMWPE samples. The thermal effect on wear was examined by differential scanning calorimeter (DSC). The results are useful to guide the application of UHMWPE for wear-resistant component design.

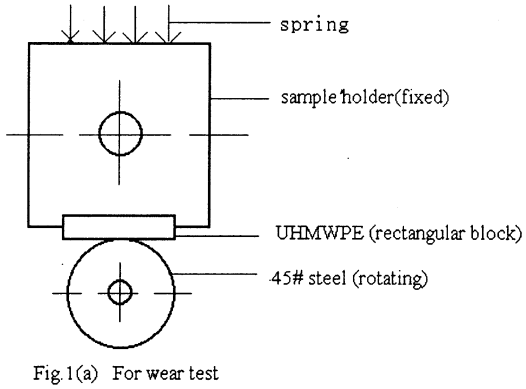

Fig.1(a) For wear test

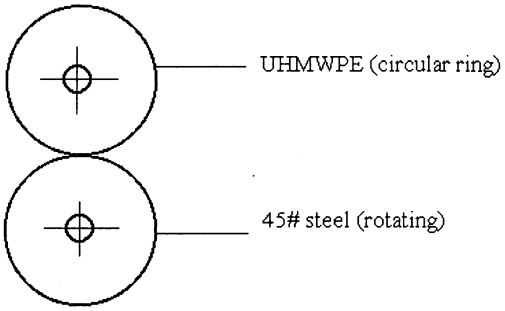

Fig.1(b) For the measurement of friction coefficient

Fig. 1. A schematic diagram of MM200 model tester under working condition.

Table 1
The physical and mechanical properties of ultra-high molecular weight polyethylene (UHMWPE)

Properties	Unit	Value
Physical properties		
Density	g cm^{-3}	0.935
Average molecular weight	g mol^{-1}	3.5×10^{6}
Absorption rate of water	%	<0.01
Mechanical properties		
Elongation of fracture	%	250
Shore D hardness		65 (~493*HV*)
Impact strength	kJ m^{-2}	150
Thermal properties		
Coefficient of swell	°C	1.5×10^{-4}
Heat deformation temperature	°C	85
Vulnerization temperature	°C	< −140

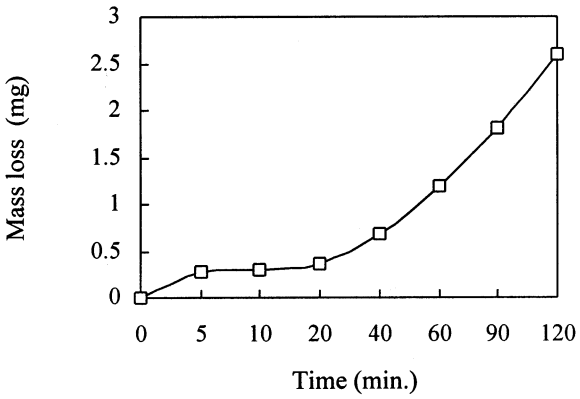

Fig. 2. The relationship between the mass loss of ultra-high molecular weight polyethylene (UHMPE) and wear time; 15 kg, 200 rev min^{-1}.

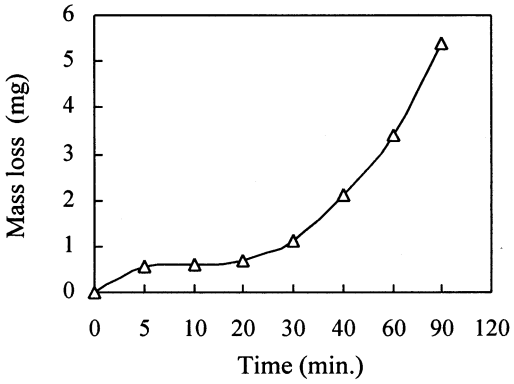

Fig. 3. The relationship between mass loss and wear time; 30 kg, 200 rev min^{-1}.

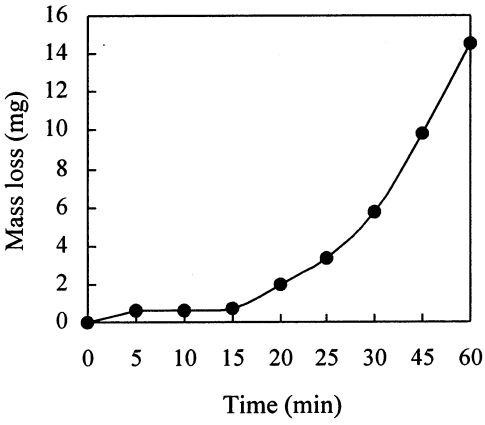

Fig. 4. The relationship between mass loss and wear time; 50 kg, 200 rev min^{-1}.

2. Experimental details

2.1. The apparatus

The sliding wear of UHMWPE was carried out on an MM200 tester (shown in Fig. 1). The tester is composed of transfer motion device, loading device, and frictional

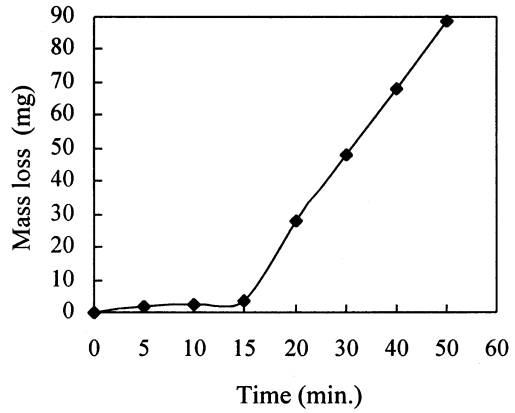

Fig. 5. The relationship between mass loss and wear time; 30 kg, 400 rev min^{-1}.

torque measuring device. The sliding pair consists of UHMWPE and 45 # steel (ASTM 1045). The upper sample is UHMWPE, and it is fixed on the sample holder. The lower sample is the 45 # steel. The contact pressure of the two samples is applied by spring. The frictional torque is measured by the swing-lever weight regulating system.

In Fig. 1(a) (for the wear test), the contact geometry changes from linear to circular as the wear test proceeds. The normal load is 15, 30 and 50 kg. The sliding is achieved by the rotation of the 45 # steel. In Fig. 1(b) (for the measurement of friction coefficient), the contact geometry remains linear during the test. The normal load is 15 and 20 kg. All the tests were carried out at an ambient temperature of 20°C.

An analytical balance was used to measure the weight loss of the polymer samples to 10^{-5} g.

2.2. Sample properties and preparation

The physical and mechanical properties of the experiment samples are given in Table 1.

The polymer samples were cut from the bulk materials in the form of rectangular block (Fig. 1(a)) and circular ring (Fig. 1(b)). UHMWPE is made into circular rings to measure the friction coefficient according to the operation manual of the MM200 tester. The sliding and rolling effects are included. In order to achieve pure sliding, a sample holder was designed and the UHMWPE was made into rectangular blocks. The size of rectangular block is 10 mm × 10 mm × 5 mm. The radius of the circular ring is 25 mm, and its thickness is 10 mm. Before the wear test, the surfaces of samples were ground with silicon carbide paper (the minimum of grit size: 7 μm), and then polished with cool polishing powder solution. The alumina slurry (the minimum of particle size: 0.25 μm) was used for UHMWPE polishing. The UHMWPE samples were then ultrasonically cleaned in alcohol and acetone until the surfaces were spotless.

The steel sample is treated by quenching and tempering. Its hardness is about HRC50. A surface finish of $R_a = 0.3$ μm (measured by a surface profilometer) was achieved for the steel specimen by hand polishing.

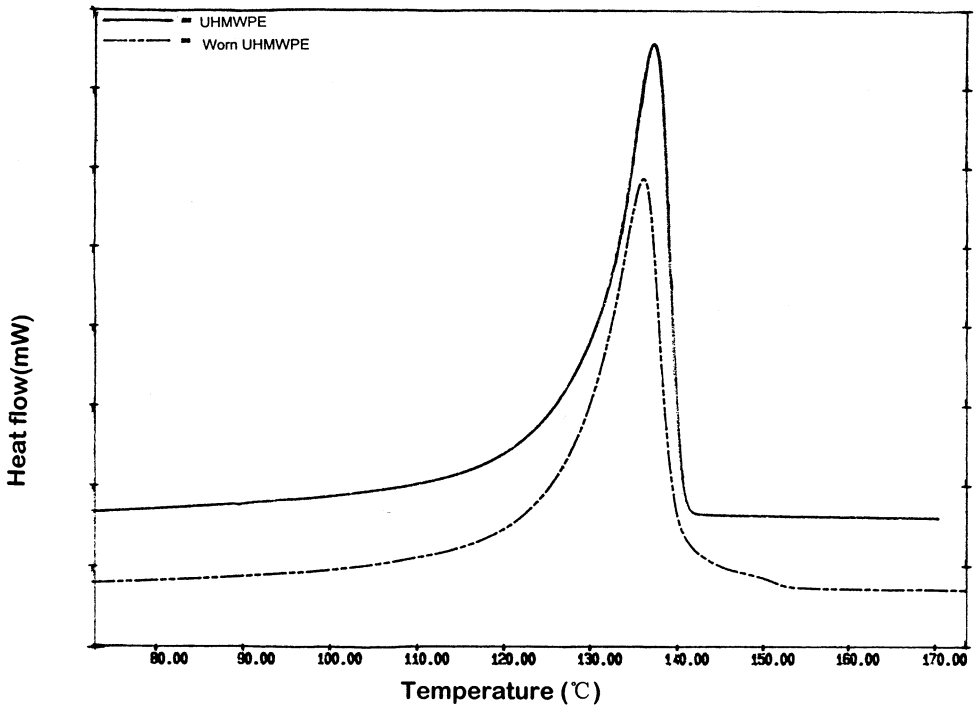

Fig. 6. Differential scanning calorimeter (DSC) curves of worn ultra-high molecular weight polyethylene (UHMWPE) and unworn UHMWPE.

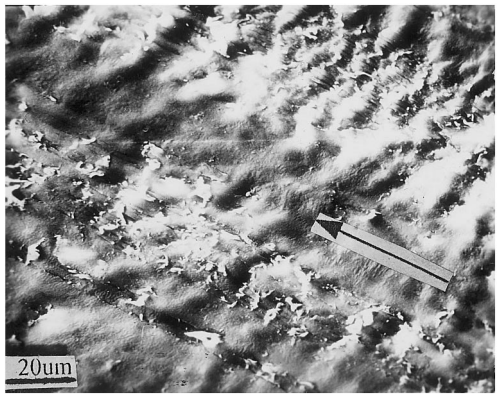

Fig. 7. Scanning electron microscopy (SEM) image of the worn ultra-high molecular weight polyethylene (UHMWPE) surface; 5 min, 30 kg, 200 rev min^{-1}. The arrow shows the sliding direction.

2.3. Experimental method

In this paper, the mass loss method was adopted to evaluate the resistance of UHMWPE to the sliding wear. Every sample was weighed three times. The experimental data was taken as the mean value of more than three tests.

In order to measure the friction coefficient of UHMWPE on the MM200 model tester, the frictional torque must be measured. The shape of UHMWPE is a circular ring and its radius is the same as its counterpart (the 45 # steel). The friction coefficient is calculated according to the formula as follows:

$$\mu = T/r \cdot p \quad (1)$$

In Eq. (1), μ represents the friction coefficient, T (kg cm) represents the frictional torque, r (cm) is the radius of the counterpart (the 45 # steel), and p (kg) is the normal load.

The worn surface morphology was observed by SEM. The surfaces were sputtered with a Au coating to render them electrically conducting, prior to the examination in the scanning electron microscope.

Microtomed films from the bulk polymer as well as the worn polymer were heated in DSC to detect any likely internal changes in the UHMWPE caused by sliding. A heating rate of 10°C min^{-1} was used for the UHMWPE. At least three scans were made per test. The degree of crystallinity of UHMWPE was calculated by assuming the heat of fusion of 100% crystalline polyethylene (ΔH_f^0) to be 293 J g^{-1}. The percentage crystallinity is then calculated from the following:

$$\% \text{ crystallinity} = (\Delta H_f/\Delta H_f^0)100\%, \quad (2)$$

where ΔH_f is the heat of fusion of the sample. Therefore, the thermal effect on the sliding wear of UHMWPE was determined by DSC examination.

3. Results

3.1. Sliding wear characteristics of UHMWPE

3.1.1. The friction coefficient of UHMWPE

When sliding against 45 # steel surface, the friction coefficient of UHMWPE is between 0.12 and 0.14 in the beginning of the wear (in about 5 min), while the friction coefficient is between 0.09 and 0.10 afterwards. This is mainly because UHMWPE contacts with the steel surface and a series of ridges are formed on the UHMWPE surface in the running-in period, while in the steady-state period, the ridges on the UHMWPE surface disappear and wear debris cover the surface and the coefficient of friction is lower. This can be proven by SEM examination. The change of load exerts limited influence on the friction coefficient.

3.1.2. The influence of sliding velocity and load on the wear loss

It can be seen from Fig. 2 that there are three periods: running-in period, steady-state period and severe wear period, respectively. In the running-in period, a series of ridges are formed on the UHMWPE surface. In the steady-state period, the ridges formed on the UHMWPE surface disappear and the wear is relatively steady. In the severe wear period, the heat accumulated in the wear process causes the thermal softening of UHMWPE, and repeated sliding causes massive tearing and rupture of the surface layer. When the load becomes 30 kg, and the sliding velocity remains unchanged, the wear loss nearly doubles, but the shape of the curve remains unchanged (Fig. 3). When the load adds up to 50 kg, the wear loss of the steady-state period is nearly the same as that under the load of 30 kg, but the wear loss of the severe wear period increases evidently. The shape of the curve is also unchanged (Fig. 4). It can be seen from Figs. 2–4 that the steady-state period becomes shorter with the increase of the load.

When the sliding velocity becomes 400 rev min^{-1} and the load is 30 kg, the wear loss increases dramatically (Fig. 5). Compared with the wear loss in Fig. 3, the rate of wear loss in the severe wear region nearly increases by an order of magnitude. From this, it can be seen that the sliding velocity shows greater influence on the wear loss than load. In the severe wear period, the shape of the curve also changes from parabola to an approximate line.

3.2. DSC analysis of the UHMWPE

The DSC curves of the bulk UHMWPE and the worn UHMWPE were presented in Fig. 6. The melting temperature of unworn UHMWPE is 137.15°C, while the melting temperature of worn UHMWPE is

135.98°C. The onset temperature of unworn UHMWPE is 129.31°C, while the onset temperature of worn UHMWPE is 127.73°C. The ΔH_f of unworn UHMWPE is 148.44 J g^{-1} and the ΔH_f of worn UHMWPE is 135.04 J g^{-1}. Thus, the percentage crystallinity can be calculated according to the Eq. (2). The percentage crystallinity of unworn UHMWPE is 50.66%, while the percentage crystallinity of the worn UHMWPE is 46.09%. The drop in melting temperature and the decrease in crystallinity are likely due to the thermal softening of UHMWPE surface layer.

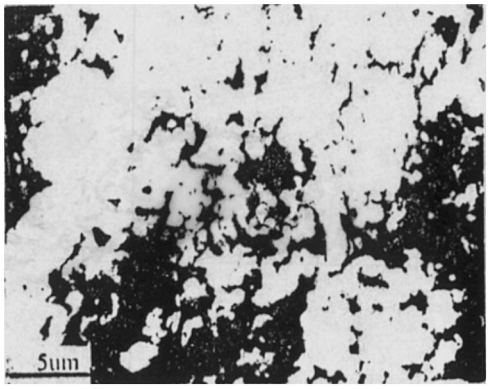

Fig. 8. Scanning electron microscopy (SEM) image of worn ultra-high molecular weight polyethylene (UHMWPE) surface; 10 min, 30 kg, 200 rev min^{-1}.

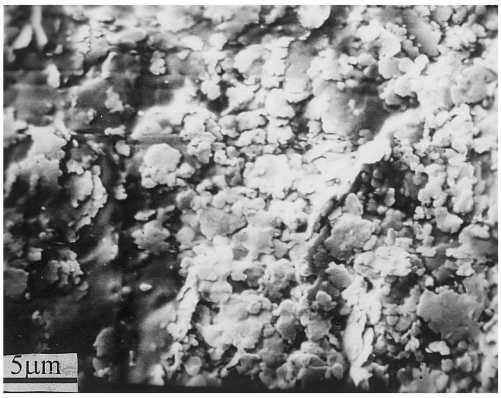

Fig. 9. Scanning electron microscopy (SEM) image of the worn ultra-high molecular weight polyethylene (UHMWPE) surface; 15 min, 15 kg, 200 rev min^{-1}.

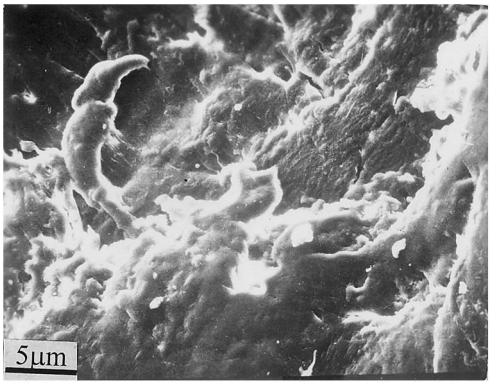

Fig. 10. Scanning electron microscopy (SEM) image of worn ultra-high molecular weight polyethylene (UHMWPE) surface; 50 min, 30 kg, 400 rev min^{-1}.

3.3. SEM analysis of the worn surfaces

It can be seen from Fig. 7 that a series of ridges are formed on UHMWPE surface in the running-in period. The ridges are normal to the sliding direction. There are also many pits caused by the repeated sliding. The ridges disappear as the wear approaches the steady-state period. Under the repeated sliding, the wear debris are reprocessed and pile together little by little (Figs. 8 and 9). The wear debris appear as flakes. From Figs. 8 and 9, the conclusion can be drawn that in the steady-state wear period, the morphology of the worn UHMWPE surfaces remains similar under different loading. When the repeated sliding causes the thermal softening of the surface layer materials, the massive tearing and rupture of UHMWPE (Fig. 10) take place. Lip-like scales are formed on the UHMWPE surface.

4. Discussion

From the literature [7,8] reported, when UHMWPE slides against metal surface, UHMWPE can form highly adherent film on the metal surface. The experimental results show that adherent thin film is formed on the metal surface.

When UHMWPE sample goes through a period time of sliding wear process, the surface appears as a yellow layer. A certain amount of heat is produced when the steel slides against the UHMWPE surface. The surface and bulk temperature is increasing as the test proceeds. When the surface temperature reaches a certain degree, thermal softening occurs and the rate of wear loss increases.

5. Conclusions

(1) In the sliding wear of UHMWPE, sliding velocity exerts greater influence on the sliding wear than the applied load.

(2) The friction coefficient of UHMWPE is between 0.12 and 0.14 in the beginning of wear, while the friction coefficient is between 0.09 and 0.10 afterwards. The change of load exerts limited influence on the friction coefficient.

(3) Three different periods can be distinguished in the wear loss versus operating time curves. They are running-in period, steady-state period and severe wear period, respectively. A series of ridges are formed in the

running-in period; in the steady-state period, the wear debris are reprocessed; the massive tearing and rupture of the surface layer has taken place in the severe wear period.

Acknowledgements

The authors wish to thank Professor X.B. Zhang and engineer A.L. Zhang for their experimental assistance.

References

[1] J.R. Atkinson, K.J. Brown, D. Dowson, J. Lubr. Technol. 100 (1978) 208–218.
[2] J.R. Atkinson, K.J. Brown, D. Dowson, J. Lubri. Technol. 104 (1982) 17–22.
[3] J.R. Cooper, D. Dowson, J. Fisher, Wear 162–164 (1993) 378–384.
[4] D. Dowson, J.M. Challen, K. Holmes, J.R. Atkinson, The influence of counterface roughness on the wear rate of polyethylene, in: D. Dowson, M. Godet, C.M. Taylor (Eds.), The Wear of Non Metallic Materials, Proc. 3rd Leeds–Lyon Symp. on Tribology, MEP, London, 1978, pp. 99–102.
[5] T.S. Barrett, G.W. Stachowiak, A.W. Batchelor, Wear 153 (1992) 31–350.
[6] B.J. Briscoe, A.K. Pogosian, D. Tabor, Wear 25 (1974) 19–34.
[7] K. Marcus, C. Allen, Wear 162–164 (1993) 1091–1102.
[8] K. Marcus, C. Allen, Wear 178 (1994) 17–28.
[9] A. Wang, D.C. Sun, C. Stark, J.H. Dumbleton, Wear 181–183 (1995) 241–249.
[10] Yu.M. Pleskachevsky, A.L. Zaitsev, V.V. Smirnov, Wear 181–183 (1995) 222–226.
[11] Karl-Heinz Zum Gahr, Microstructure and Wear of Materials, Elsevier, Amsterdam, 1987, p. 292.
[12] C.M. Pooley, D. Tabor, Proc. R. Soc. Lond., Ser. A 329 (1972) 251–274.
[13] J.K.A. Amuzu, B.J. Briscoe, D. Tabor, Polymers as bearings and lubricants: aspects of fundamental research, Advances in Tribology, Inst. Mech. Eng., London, 1978, pp. 59–62.