

Investigation of the friction and wear behaviors of polyoxymethylene/linear low-density polyethylene/ethylene-acrylic-acid blends

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Abstract

The friction and wear behavior of polyoxymethylene/linear low-density polyethylene/ethylene-acrylic acid (POM/LLDPE/EAA) blends is explored using an MM-200 wear tester. The results show that the friction and wear properties of POM were greatly improved after an amount of LLDPE and EAA was added. The friction coefficient and wear scar width of POM are much higher than those of POM/LLDPE/EAA blends under the same condition. The SEM analyses show that POM and POM/LLDPE/EAA blends exhibit totally different wear mechanisms. The wear mechanism of POM is dominated by adhesive. The transfer film of POM is formed on the surface of the steel counterpart. For POM/LLDPE/EAA blend, the lamellar debris is found on the steel ring surface sliding against POM/LLDPE/EAA blend, which helps to decrease the friction coefficient and wear scar width. The lubricate layer formed in the contact surface prevents the bulk from serious wear. Therefore the friction coefficient of POM/LLDPE/EAA blend thus reduced remarkably and anti-wear property got greatly improved.

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1. Introduction

Polyoxymethylene (POM) exhibits low friction coefficient, low wear rate and a unique balance of mechanical, thermal, chemical and electrical property [1,2]. Therefore POM is applied as a construction material, e.g. mechanical and electromechanical fabricate, electronic parts, precision instrument gears, bearing liners and rings. However, the pure POM resins cannot necessarily satisfy the requirements as sliding parts only by the abrasion resistance that they inherently possess. Especially under high load and high sliding speed, the friction coefficient of POM against the steel ring increases, resulting in the increasing of the abrasion wear. Consequently, further improvement in friction and wear properties of POM is necessary.

To improve the wear resistance and decrease the friction coefficient of POM, many authors generally added PTFE [3–6], silicone oil [7,8], UHMWPE [9,10], etc., as lubricate component

in POM. PTFE exhibits very low coefficients of friction, and it can easily form a thin film on the contact surface in the polymer composites, which helps to decrease the friction coefficient and wear rate. But Fine PTFE powder has a strong tendency to agglomerate and therefore it is very difficult to disperse the powder into highly viscous polymer melts. The adhesion between POM and PTFE is very weak. This makes the mechanical properties of POM/PTFE composites very poor. In addition, the cost of a composite material must be considered. The higher price of PTFE will increase the cost of POM/PTFE composites. While infusion of silicone oils and other lubricating oils into POM in amounts is sufficient to optimise the tribological properties of the composition, it has been found to impair the ability to process these compositions into useful objects by extrusion or injection molding. This problem arises due to the inherent immiscibility of POM and most lubricating oils. Moreover, in the above-mentioned modified methods, there remain the disadvantages of poor dispersibility in the POM matrix, an insufficient improvement of the friction and wear properties, and poor mechanical strength, due to the high viscosity and large particle sizes of these materials. Accordingly, it is necessary to prepare POM

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blends having excellent friction and wear behaviors as well as well-balanced mechanical properties.

Polyethylene (PE) exhibits better toughness, processability and moldability than POM. In addition, PE also possesses lower price than other modifying agents. Now many efforts have been made to apply low molecular weight polyethylene (e.g. polyethylene wax), HDPE and UHMWPE to improve the friction and wear properties of POM. But little work has been concerned with the tribological investigation of POM blending with linear low-density polyethylene (LLDPE). In this work, we try to examine the friction and wear behaviors of POM/LLDPE/EAA blends, where EAA is added as a compatibilizer.

2. Experimental

2.1. Materials

Chemically pure polyoxymethylene copolymer granular (designated as M90; specific gravity = 1.41 g/cm³) was provided by Yunnan Yuntianhua Co., China, with a MFI = 9.0 g/min (190 °C, 2.16 kg). LLDPE (QLLM-06) characterized by a melt index of 5.4 g/10 min (190 °C, 2.16 kg) was kindly donated from Qilu Petrochemical Co., China. EAA (primoacor 1410) characterized by a melt index of 1.5 g/10 min (190 °C, 2.16 kg) was purchased from Dow Plastic Co., USA.

2.2. Sample preparation

All blends were prepared on a twin-screw extruder ($D = 15$ mm, $L/D = 22$; SHJ-20, Nanjing Giant Co., China) with the die temperature 175 °C. POM was dried in an air oven for 2 h at 80 °C to remove water before extrusion. The blank POM was also processed under the same extrusion conditions to give a thermal history similar to that of the blends samples. The materials thus prepared were injection molded by an injection molding machine (K-TEC 40, Germany) at the barrel temperatures between 175 and 195 °C.

2.3. Friction and wear testing

The friction and wear tests were conducted on a MM-200 friction and wear tester (Shanghai, China) at room temperature according to GB3960-83. The diameter of the steel ring (45# steel) is 40 mm and the surface roughness (R_a) is 0.015 μ m. The dimension of the specimen is 30 mm \times 6 mm \times 7 mm. The rotation speed of the steel ring is 200 and 400 rpm during operation. Load and time applied were set by tests. Friction torques (T) was

recorded every 5 min, and the friction coefficient was calculated by equation as follows:

$$\mu_\alpha = \frac{T_\alpha}{MR} \quad (1)$$

μ_α is the average friction coefficient, T_α the average friction torque (kg cm), M the load (kg), and R is the radius of the steel ring (cm).

Wear scar width of specimens was adopted to evaluate anti-wear property. Three replicate tests were carried out for each specimen. Before the testing, the steel ring and the specimen were washed with acetone and dried naturally.

2.4. Morphology observation

A JSM-5900LV scanning electron microscope (Japan) was used to observe the worn surface and the morphology of wear debris. Atomic Force Micrograph (SPA400, Seiko Japan) measuring with contacting mode was applied to investigate the worn surface of specimens and measure the micro-friction force.

3. Results and discussion

3.1. Mechanical properties

Mechanical properties of the blends are listed in Table 1. The impact strength of POM decreases from 8.75 to 4.18 kJ/m² after 10 wt.% LLDPE is added. The impact strength of POM/LLDPE blend is raised to 6.70 kJ/m² after 4 wt.% EAA adding. This can result from the addition of EAA improved the compatibility between POM and LLDPE.

The brittle fracture surface morphology of POM/LLDPE/EAA blends in the liquid nitrogen observed by SEM, are shown in Fig. 1. The binary blend of POM/EAA exhibits well dispersion of EAA domains (Fig. 1B). This can be attributed to the good compatibility between POM and EAA. Compared to Fig. 1C, it can be seen from Fig. 1D that the dispersion of LLDPE domains is more uniform and the LLDPE domain size is smaller after EAA is added to POM/LLDPE blends. These result in the improvement of mechanical properties of POM/LLDPE/EAA blends.

3.2. Friction and wear behaviors

The dependence of the friction coefficient of POM/LLDPE/EAA blends on the weight fraction of LLDPE and EAA is showed in Fig. 2. The friction coefficient of POM/LLDPE/EAA

Table 1
Mechanical property of various specimens

Specimens	Mechanical properties			
	Notched izod-impact strength (kJ/m ²)	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (MPa)
POM	8.75	58.0	41.33	2396
POM/EAA (100/4)	8.15	56.6	51.35	2106
POM/LLDPE (90/10)	4.18	48.5	37.27	1677
POM/LLDPE/EAA (86/10/4)	6.70	46.7	40.54	1714

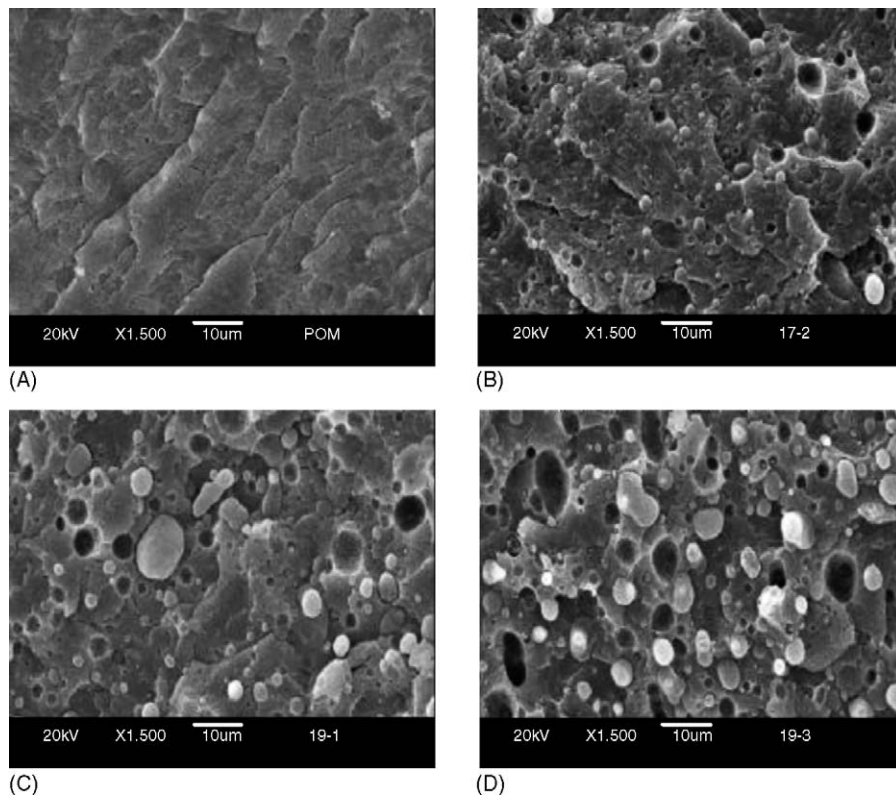


Fig. 1. Morphology of fractured surface of POM and POM blends: (A) POM; (B) $w(\text{POM}/\text{EAA})=100/4$; (C) $w(\text{POM}/\text{LLDPE})=90/10$, $w(\text{EAA})=0\%$; (D) $w(\text{POM}/\text{LLDPE})=90/10$, $w(\text{EAA})=4\%$.

blends decreases remarkably with increasing the LLDPE and EAA contents when LLDPE concentration is lower than 10%. The lowest friction coefficient reaches 0.14 when the weight fraction of POM/LLDPE/EAA blend is 86/10/4. A further increase of LLDPE content results in the increase of the friction coefficient of the blends.

Fig. 3 shows the wear scar width of the blends as a function of the content of LLDPE and EAA during sliding. Wear scar width

of POM/LLDPE/EAA (86/10/4) blend decreases from 5.00 to 3.88 mm compared to POM. After the LLDPE content is over 10%, wear scar width of POM/LLDPE/EAA blends is up as increasing the LLDPE contents.

Fig. 4 reveals that the relationship between the friction and wear properties and the contents of LLDPE in POM/LLDPE/EAA blends under the high-speed condition (400 rpm), where the EAA content is fixed at 4%. The results

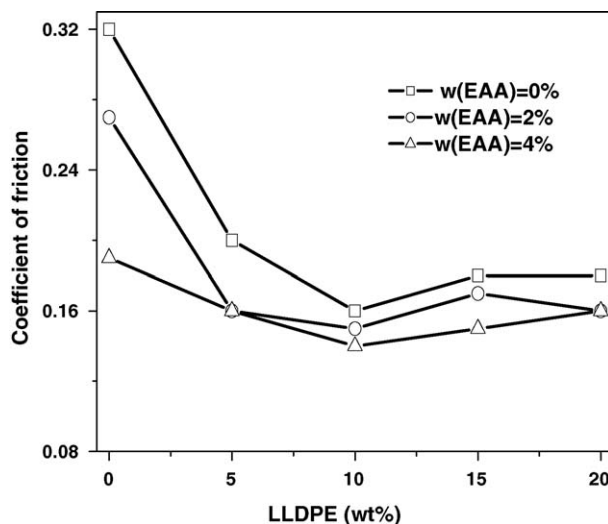


Fig. 2. Variation of coefficient of friction with LLDPE contents in POM/LLDPE/EAA blends (speed: 200 rpm, load: 30 kg, time: 30 min).

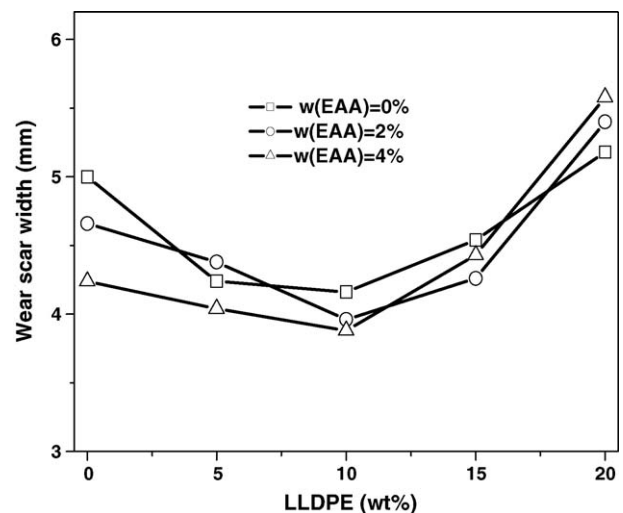


Fig. 3. Variation of wear scar width with the LLDPE content in POM/LLDPE/EAA blends (speed: 200 rpm, load: 30 kg, time: 30 min).

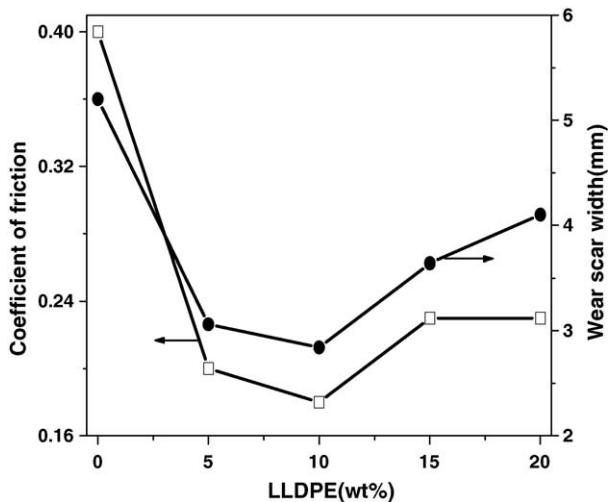


Fig. 4. Variation of friction and wear properties with LLDPE content in POM/LLDPE/EAA blends (EAA = 4 wt.%) (speed: 400 rpm, load: 10 kg, time: 20 min).

indicate that when the content of LLDPE is lower than 10%, the friction coefficient and wear scar width of the blend decrease with increasing the LLDPE weight fraction. A further increase of LLDPE concentration results in the increase of the friction coefficient and the wear scar width of the blends.

Wear scar width of POM and POM/LLDPE/EAA blend increases with sliding time. The wear scar widths of POM are higher than those of POM/LLDPE/EAA blend (Fig. 5). The wear of POM is much more sensitive to sliding time than that of POM/LLDPE/EAA blend. The increase of wear scar width of POM with wear time is much sharper than those of POM/LLDPE/EAA blends. Wear scar width increase from 5.00 mm (30 min) to 7.46 mm (120 min) of POM, compared with that from 3.88 to 4.44 mm of the POM/LLDPE/EAA blend under the same condition.

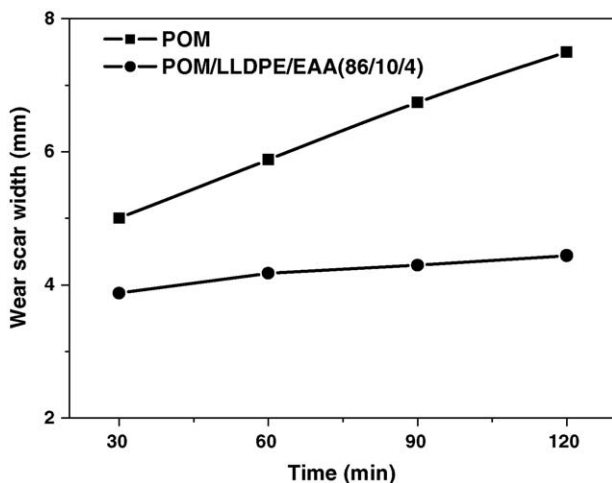


Fig. 5. Variation of wear scar width of specimens with time (speed: 200 rpm, load: 30 kg).

3.3. Investigation of wear mechanism

Fig. 6 reveals the scanning electron micrographs of the worn surface of POM under various conditions. Many scratch grooves parallel to the sliding direction are clearly observed in the worn surface of POM when POM sliding against the steel counterpart (Fig. 6A). Obvious long scratches in the worn surface of POM indicate that POM undergoes abrasive and adhesion wear. With the increase of wear time, the phenomenon of thermal softening and melting is presented in the worn surface of POM (Fig. 6B). The worse of the worn surface with the increase of time is consistent with the friction and wear data discussed above.

Fig. 7 shows that the morphologies of the worn surface of POM/LLDPE/EAA blend are quite different from those of POM. Obvious plastic deformation is observed in the worn surface of POM/LLDPE/EAA blend during sliding (Fig. 7A). With sliding time increasing, some wear debris is found in the worn surface (Fig. 7B). The wear debris isolates the contact between the steel and POM/LLDPE/EAA blend matrix, acting as rolling lubricants. Therefore the friction and wear properties of POM are improved effectively. It can be seen from Fig. 7C that the contact surface seems to be covered by a lubricant film, which prevents the bulk from serious wear.

Fig. 8 reveals typical SEM images of the steel counterpart surface. A discontinuous transfer layer is formed on the steel ring surface when the steel counter-face sliding against POM (Fig. 8A). The transferred film is brown and adheres firmly to the steel ring surface due to serious oxidization. In Fig. 8B, wear debris and lubricant film can be also seen on the steel counterpart surface when sliding against POM/LLDPE/EAA blend. Wear debris and the lubricant layer existed in the worn surface are the main reason leading to improving the friction and wear properties of POM/LLDPE/EAA blend.

SEM of the worn surface of POM and POM/LLDPE/EAA blend under the high-speed condition (400 rpm) are shown in Fig. 9. The removal of melted polymer from POM matrix occurs in the worn surface during sliding (Fig. 9A). Thermal softening or melting of the worn surface of POM indicates that the temperature of the contact area has approached to the softening point of POM. On the contrary, no such serious damage is observed on the worn surface of POM/LLDPE/EAA blend (Fig. 9B). Obvious plastic deformation and wear debris are observed on the worn surface of POM/LLDPE/EAA blend.

Under the high sliding speed, there is the great effect of the temperature of worn surface on the wear of polymer materials due to the poor thermal conduction of polymers. The temperature of the worn surface is up because of the friction heat produced. POM appears to wear by continuous deformation favored by thermal softening or melting (Figs. 5B and 9A). Thus, POM exhibited the worse friction and wear properties at high sliding speed.

The above results indicate that wear debris play an important role in improving the friction and wear behavior of POM/LLDPE/EAA blends. It was predicted that there was some internal difference in the wear mechanisms of POM and POM blends. Owing to the fact that the wear debris originating from

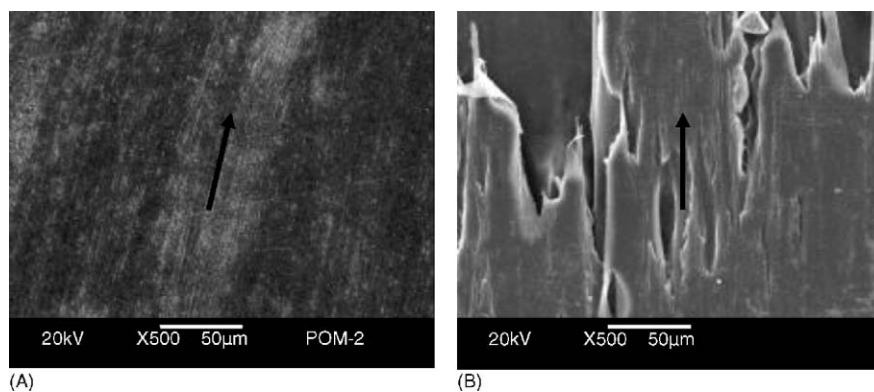


Fig. 6. Scanning electron micrographs of the worn surface of POM (A, speed: 200 rpm, load: 30 kg, time: 60 min; B, speed: 200 rpm, load: 30 kg, time: 120 min).

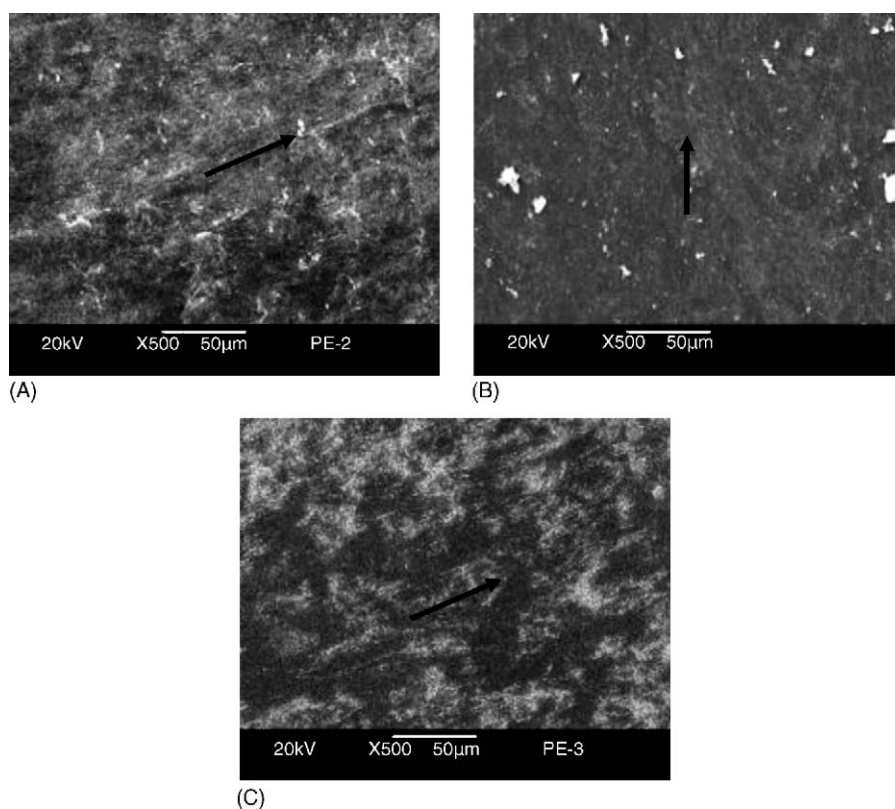


Fig. 7. SEM of the worn surface of POM/LLDPE/EAA (86/10/4) (A, speed: 200 rpm, load: 30 kg, time: 60 min; B, speed: 200 rpm, load: 30 kg, time: 120 min; C, speed: 200 rpm, load: 30 kg, time: 180 min).

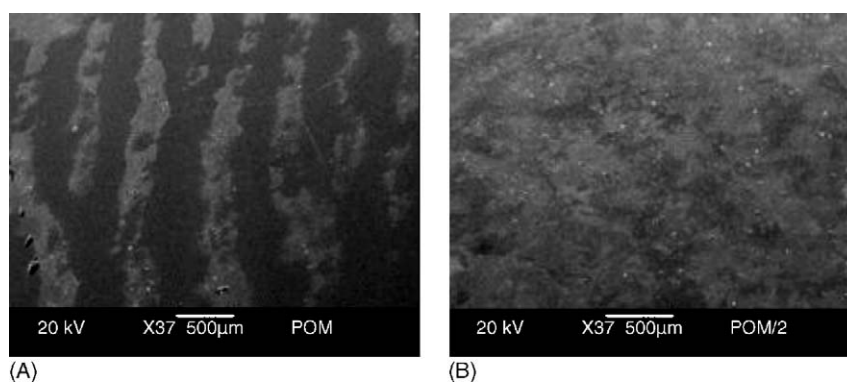


Fig. 8. SEM of the steel counterpart surface sliding against POM (A) and POM/LLDPE/EAA (86/10/4) blend (B) (speed: 200 rpm; load: 30 kg; time: 120 min).

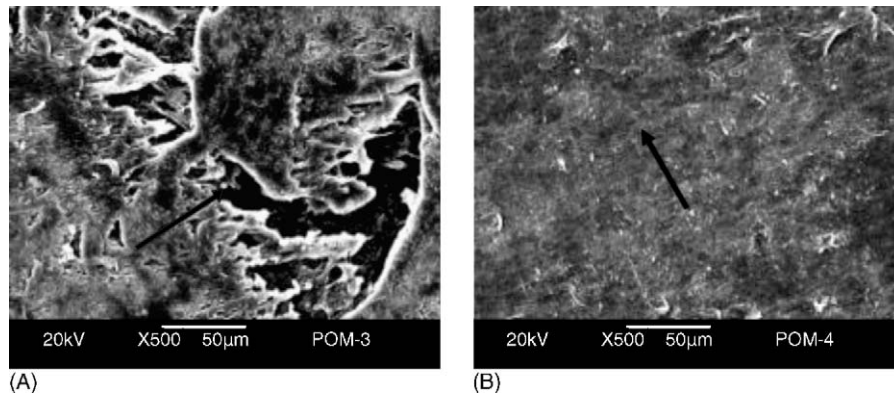


Fig. 9. SEM of the worn surface of POM (A) and POM/LLDPE/EAA (86/10/4) (B) (speed: 400 rpm, load: 10 kg, time: 30 min).

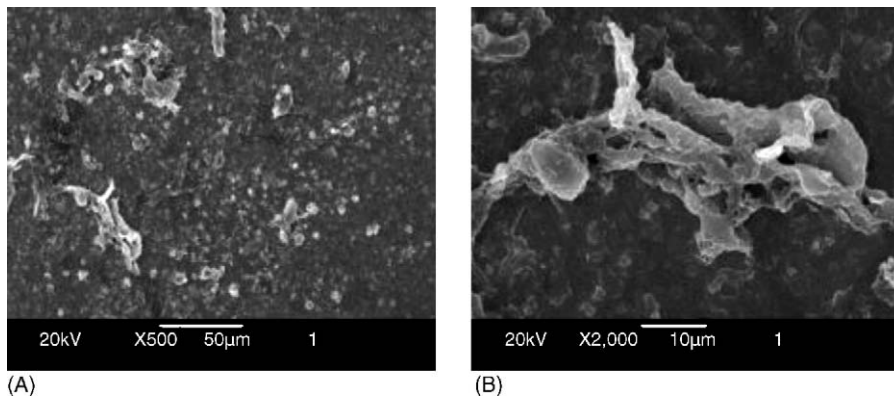


Fig. 10. SEM micrographs of the POM/LLDPE/EAA blend wear debris produced during sliding (speed: 200 rpm, load: 30 kg, time: 120 min).

the polymer surface experienced complicated interaction of the steel counterpart, the different debris morphologies should be the results of different wear mechanisms. Generally, the granular particles including the rod-like and block-like debris can be attributed to an abrasive micro-cutting effect [11]. On the other hand, fatigue delamination was also an important wear mechanism, which was usually considered to be responsible for the debris in the form of sheets [12,13]. Therefore, we carry out a general survey of the SEM analysis of the collected wear

debris. It can be seen from Fig. 10A that all fragments of wear debris exhibit different morphology, unequal dimensions and irregular shapes. Their appearances and sizes distribution look rather different at first glance, in spite of the fact that the particles were produced under the same conditions. Further magnification observations can find that wear debris exhibits lamellar structure and uneven edges, indicative of plastically stretching and resin melting duration formation (Fig. 10B). This indicates that the formation of lubricant layer is just due to the molten of the

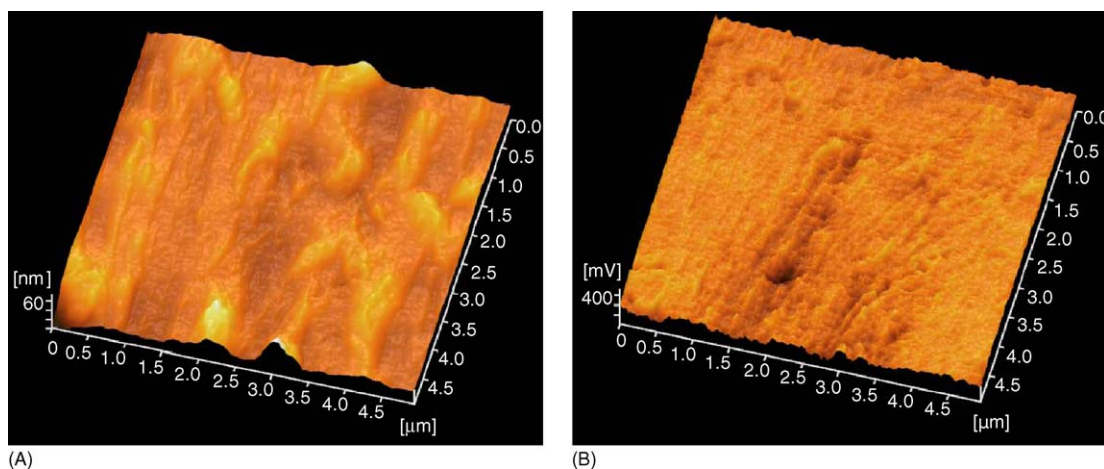


Fig. 11. Topographic (A) and friction image (B) of POM (force reference: -0.176 nN, scan rate: $8 \mu\text{m/s}$).

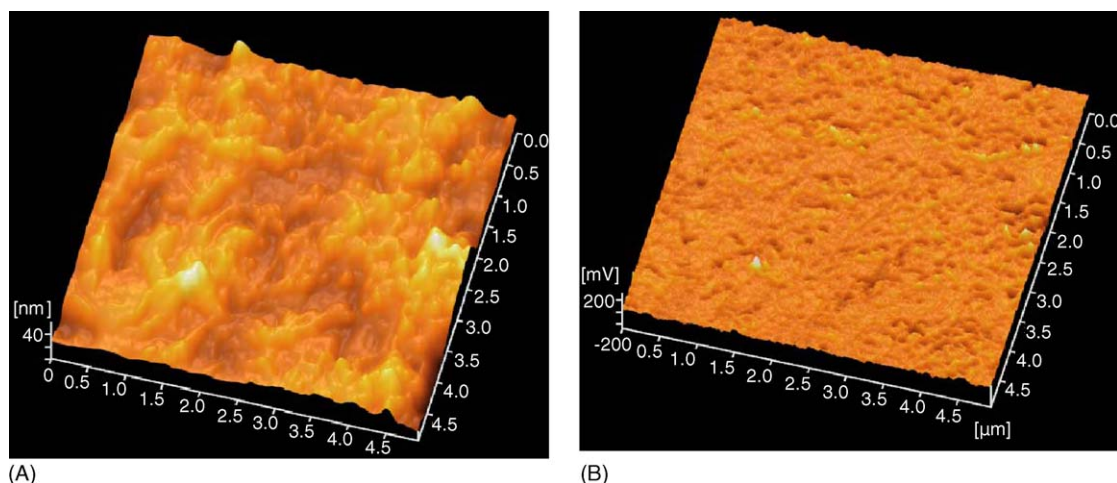


Fig. 12. Topographic (A) and friction image (B) of POM/LLDPE/EAA (force reference: -0.176 nN, scan rate: $8 \mu\text{m/s}$).

wear debris. Previous work [14] we had studied showed the wear debris originated from LLDPE transferring to the worn surface during sliding. Because the melt point of LLDPE is lower than that of POM, wear debris would melt first and form the lubricant layer in the worn surface after a long time sliding.

AFM observation of the worn surface (200 rpm, 30 kg, 120 min) of POM and POM/LLDPE/EAA (86/10/4) blend are shown in Figs. 11 and 12, respectively. The irregular grooves can be observed in the worn surface of POM from Fig. 11A. The surface topography of POM/LLDPE/EAA blend (Fig. 12A) seems more uniform compared to POM. While the friction force of POM/LLDPE/EAA blend is much less than that of POM and varied slightly over the scan area (Figs. 11B and 12B). The difference micro-friction behavior of pure POM and POM/LLDPE/EAA blend from AFM is well consistent with the results from the macro-friction study discussed above. Of course, the friction force evaluated from AFM is rather different from the macro-friction behavior. It is not clear whether the friction data from AFM can correlate direct with the macro-friction properties, which needs to be further verified.

4. Conclusion

From the above results, the following conclusions could be drawn:

- (1) POM and POM/LLDPE/EAA blends exhibit totally different friction and wear behaviors. The friction coefficient and the wear rate of POM/LLDPE/EAA blends are much lower than those of POM under the same condition.
- (2) When sliding against the stainless steel, POM appears to wear by thermal softening or melting of the surface layer materials. Transferred film is formed in the steel counterpart after a long sliding time. The wear of POM is similar to adhesion wear and fatigue wear.
- (3) For POM/LLDPE/EAA blends, wear debris could be found on the steel counterpart surface during sliding. Wear debris, as rolling lubricants, decreased effectively the fric-

tion coefficient and wear scar width. The lubricate layer formed because of the melting of wear debris after a long sliding time effectively helped to prevent the bulk from serious wear. Therefore the friction coefficient of POM/LLDPE/EAA blend was thus reduced remarkably and anti-wear property got greatly improved even after a long time sliding.

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