Effect of Structure on the Tribological Properties of Polytetrafluoroethylene Drawn Uniaxially at the Melting Point

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ABSTRACT: Drawn polytetrafluoroethylene (PTFE) with different draw ratio and sliding directions were investigated using a pin-on-disc tester. The anisotropy of tribological properties for drawn PTFE was found and the lowest friction coefficient and wear rate were reached when sliding along draw direction. The higher the orientation degree was, the smaller the friction coefficient and the wear rate were. The morphologies of the samples and debris were characterized by scanning electron microscope. The results showed that the fiber structure of drawn PTFE was formed and the morphologies of debris were different from undrawn PTFE. The results indicated that the bulk orientation structure of drawn PTFE played an important role on its tribological properties. The shear force was parallel with the oriented fibrils formed by drawing when sliding along draw direction and a better smoothing worn surface occurred easily, which resulted in the low friction coefficient. The fiber formed by drawing prevented effectively the large flake-like debris from formation, which reduced the wear rate of drawn PTFE. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 106: 1332–1336, 2007

Key words: polytetrafluoroethylene (PTFE); drawing; fiber; orientation; tribology

INTRODUCTION

Polytetrafluoroethylene (PTFE) has been proved to be an outstanding material of great importance because of its many good properties, such as very high melting point, extreme resistance to solvents and corrosive agents, unique nonadhesion and very low friction coefficient. The wear behavior has drawn considerable interest in the past years.[1] Many studies of the frictional properties of PTFE have been reported by Tabor and coworkers[2,3] However, most of the works concentrated on the influence of testing parameters (such as speed, pressure, temperature, humidity, and the kind of the counterparts) on the wear rate and the effect of fillers on the tribological properties of PTFE.[4–9] For example, it was found by McNicol et al. that the wear of PTFE showed a strong dependence on humidity.[8] Viswanath and Bellow found that the composition and structure of fluorocarbon affect its wear, but the wear behavior is independent of the counterface.[9] Smurugovet et al. suggested that PTFE worn to be associated most of all with the breaking of weak intermolecular bonds and with interplanar shear and slipping of crystalline aggregates formed in the band structure of the material. Adhesional forces between the contacting surfaces and the effect of temperature on the rheological properties of PTFE film affect the friction coefficient.[4]

That the oriented structures of polymer influence the tribological properties was also observed by researchers.[10,11] A slight but quite definite directional effect was observed by Tabor and Wynne Williams with PTFE which was attributed to its unique ability to form a highly crystalline state.[12] Li et al. have reported that the debris with long fibers was produced under high temperature.[13] Chang et al. studied the wear behavior of bulk oriented and fiber reinforced UHMWPE.[14] However, little attention has been paid to the effect of the structure of drawn PTFE on the tribological properties.

In this article, PTFE that is crystallizable and easily oriented was selected as bulk material. The directional dependence of tribological behaviors of drawn PTFE was investigated using a pin-on-disc tester. The analysis of scanning electron microscopy (SEM) was carried out to clarify the mechanisms how the bulk orientation influences the tribological properties of PTFE. The study will give basic knowledge to understand the tribological behavior of polymer materials, which is very important for the application of polymer materials in industrial fields.

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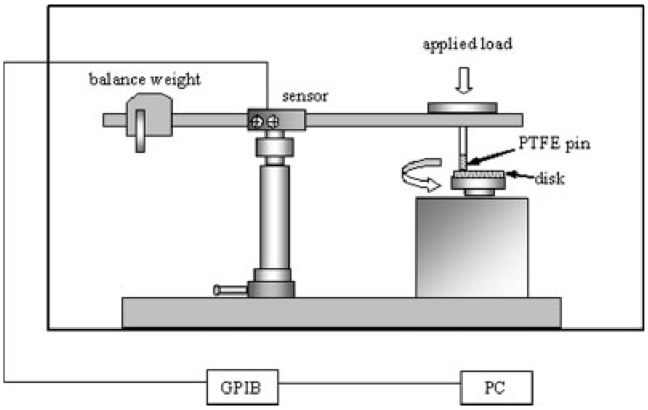


Figure 1 Schematic diagram of the tribometer.

EXPERIMENTAL

Materials

PTFE powder was molded under 30 MPa at room temperature. The molded sticks were sintered at 375°C for about 2 h, and then cooled slowly to room temperature. The sintered PTFE was machined to dumbbell shape, and was drawn at its melting point of 327°C using a stretching apparatus constructed in our laboratory. The elongated PTFE was cooled in air to room temperature. Except for special indication, data reported in this article were the results of the sample with a draw ratio of four.

Friction and wear tests

Friction and wear tests were conducted using a pin-on-disc wear tester (Fig. 1). A stainless steel disk (1Cr18Ni9Ti) was used as the counterpart (φ20 mm × 2.5 mm), which was sliding against the PTFE pin with the sizes of 2.0 mm × 1.4 mm × 2.5 mm. Sliding tests were performed under ambient conditions [temperature: 25°C, humidity: (50 ± 10)%] at a sliding velocity of 0.42 m/s and a normal load of 1.96 N. The friction coefficient was recorded automatically by an attached computer. Before each test, the disc surfaces were polished with metallographic abrasive paper to surface roughness R_a of 0.12 μm. Both pin and disc specimens were cleaned in acetone using an ultrasonic bath and then thoroughly dried. The wear rate W_s (mm^3/N m) of each specimen was calculated from the following relationship:

$$W_s = \frac{\Delta m}{L\rho F},$$

where Δm is the mass loss, L the sliding distance, ρ the density of PTFE, and F the applied load.

The sliding tests of the drawn PTFE were carried out in three different sliding directions. Figure 2 shows the draw and friction directions of PTFE. P denotes the sliding direction parallel with the draw direction. AP is the sliding direction transverse to the draw direction but also lying in the draw plane. N indicates the end plane, on which the sliding direction is perpendicular to the draw direction.

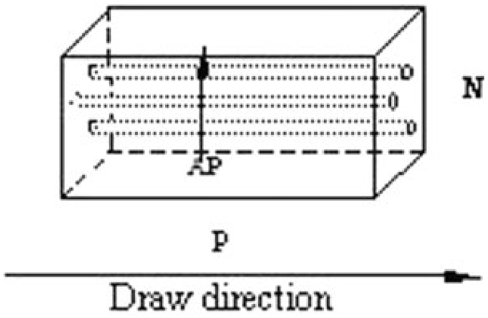


Figure 2 Schematic diagram of the friction directions for drawn PTFE (P stands for draw direction).

SEM and DSC analyses

PTFE fractured surfaces and debris were observed using SEM (JSM-5600LV, GEOL Co.). Gold-palladium alloy film was sputtered on the surfaces prior to observation. The crystallinity of samples was detected using DSC (DSC204, NETZSCH). The samples (2–3 mg) were stacked in aluminum pans with pierced lid. The measurements were conducted under nitrogen atmosphere at a heating rate of 10°C/min up to 380°C and maintained 380°C for 5 min to remove previous history, and then dropped to 20°C at a cooling rate of 10°C/min.

RESULTS AND DISCUSSION

SEM and DSC analyses

SEM images of the fractured surfaces of undrawn and drawn PTFE are given in Figures 3 and 4. No orienta-

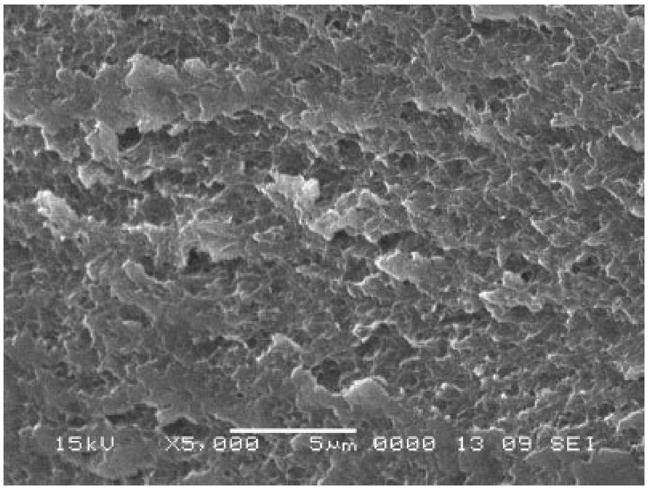
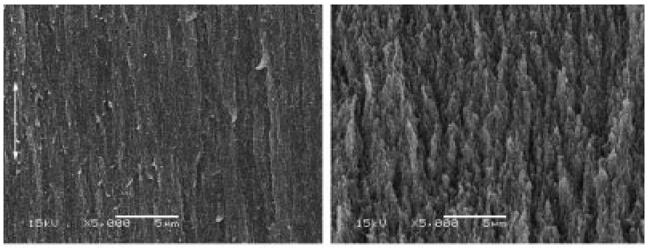
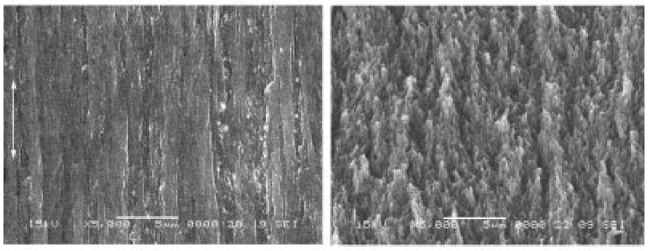


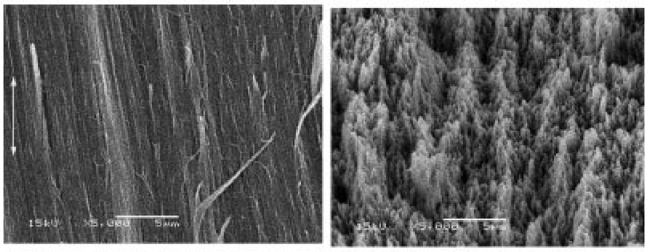
Figure 3 SEM image of fractured surface of undrawn PTFE.



(a) Draw ratio-3 (b) Draw ratio-3



(c) Draw ratio-4 (d) Draw ratio-4



(e) Draw ratio-7 (f) Draw ratio-7

Figure 4 SEM images of fractured surfaces of drawn PTFE with different draw ratios (the arrow indicates the draw direction). (a, c, e): parallel to the draw direction; (b, d, f): perpendicular to the draw direction.

tion is observed for undrawn PTFE (Fig. 3). In contrast, fiber structure seems to be formed completely for drawn PTFE [Fig. 4(a,c,e): fractured surfaces parallel to the draw direction; Fig. 4(b,d,f): the cross sections perpendicular to the draw direction]. The aligned fibrils on the whole surface are parallel with the draw direction, and they gather together to form fiber bundle. With draw ratio increasing the fibrillation degree of drawn PTFE increases as shown in Figure 4.

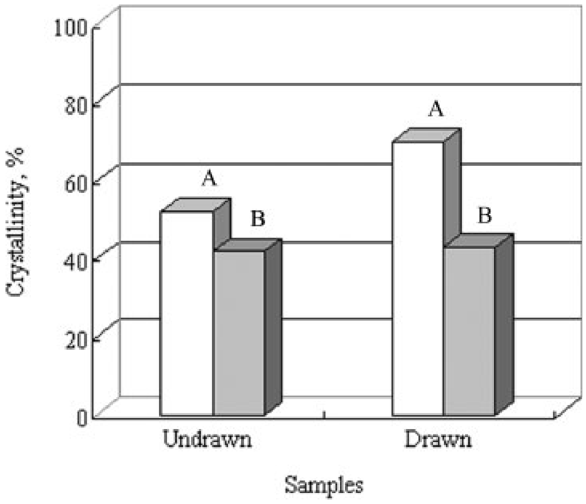
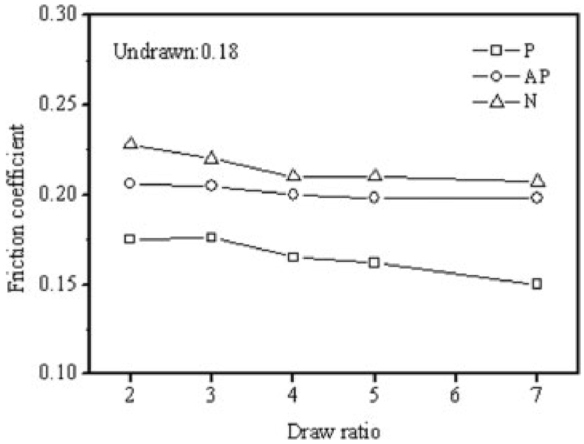


Figure 5 The crystallinity of undrawn and drawn samples. A: Before removing previous history. B: After removing previous history.

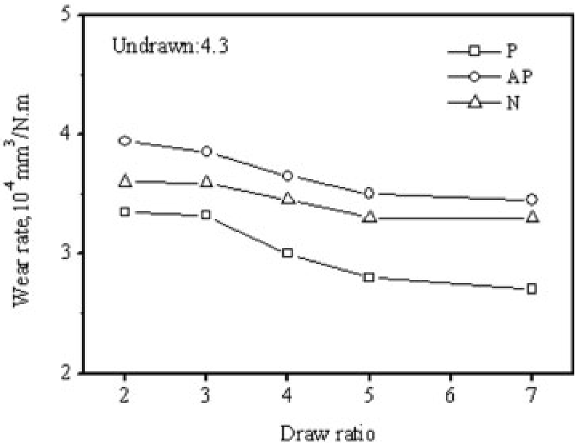
The undrawn and drawn PTFE with the draw ratio about four are analyzed using DSC to explore the variation of crystallinity. Figure 5 shows the analytical results. The crystallinity of bulk drawn PTFE is higher than that of undrawn PTFE by about 20% before removing previous history. However, the crystallinity of those two samples is almost the same after removing previous history. This result indicates that drawing can increase the crystallinity of PTFE, which is agreement with Yamaguchi's results.[10]

Friction and wear properties

The tribological behaviors of PTFE specimens are investigated to understand the effect of bulk orienta-



(a) Friction coefficient



(b) Wear rate

Figure 6 Variations in friction coefficient (a) and wear rate (b) of drawn PTFE with increasing draw ratio.

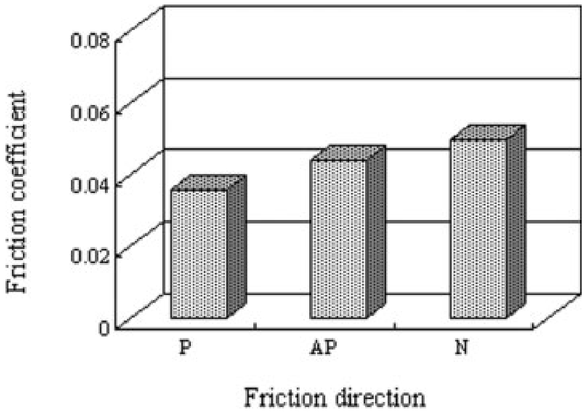


Figure 7 Friction coefficient of drawn PTFE under water lubrication.

tion structure on the tribological properties of drawn PTFE. The variations in friction coefficient and wear rate with draw ratio are shown in Figure 6. It is noteworthy that the friction coefficient is dependent on sliding direction, which has the following order: P < Un < AP < N. When sliding in P direction, higher draw ratio associates with lower friction, especially the draw ratio is higher than four. When the draw ratio is seven, the lower friction coefficient of 0.15 is reached and it is lower than undrawn PTFE by about 15%. While in AP and N direction, there is no obvious variation in friction coefficient with increasing draw ratio. The improvement in the wear resistance of drawn PTFE is observed at any sliding direction compared with undrawn PTFE, and shows the following order: P < N < AP < Un. The higher the draw ratio is, the lower the wear rate is. When the draw ratio is seven, the wear rate is lower than that of undraw PTFE by about 40% in P direction.

To make clear the anisotropy of tribological properties, the friction coefficient of drawn PTFE under water lubrication are investigated. The lubricant media are added to the frictional surface through a water hole during testing at a rate of 10 drops per minute. Figure 7 shows the friction coefficient of drawn PTFE under water lubrication. It can be seen from Figure 7 that the anisotropy of friction coefficient for drawn PTFE under water lubrication is still obvious, which has the same order as under dry sliding conditions: P < AP < N. At the same sliding direction, the friction coefficient under water lubrication is low as compared with under dry sliding condition. Those results indicate that the fiber structure formed by drawing takes part in the sliding process, which results in the anisotropy of tribological properties. It can be concluded that bulk orientation structure of PTFE plays an important role on its tribological properties.

SEM analysis of debris

Figure 8 depicts the morphologies of the debris of undrawn and drawn PTFE by SEM. It can be seen from lower magnification that the debris of undrawn PTFE [Fig. 8(a)] is flake. The debris morphologies of drawn PTFE are member-like and it is very different from that of undrawn PTFE. However (seen from higher magnification), the fibril structure of debris in P and AP directions [Fig. 8(f,g)] is obvious. Wear is a shear process either on the surface or in the bulk. Combined with the morphologies of fractured surfaces

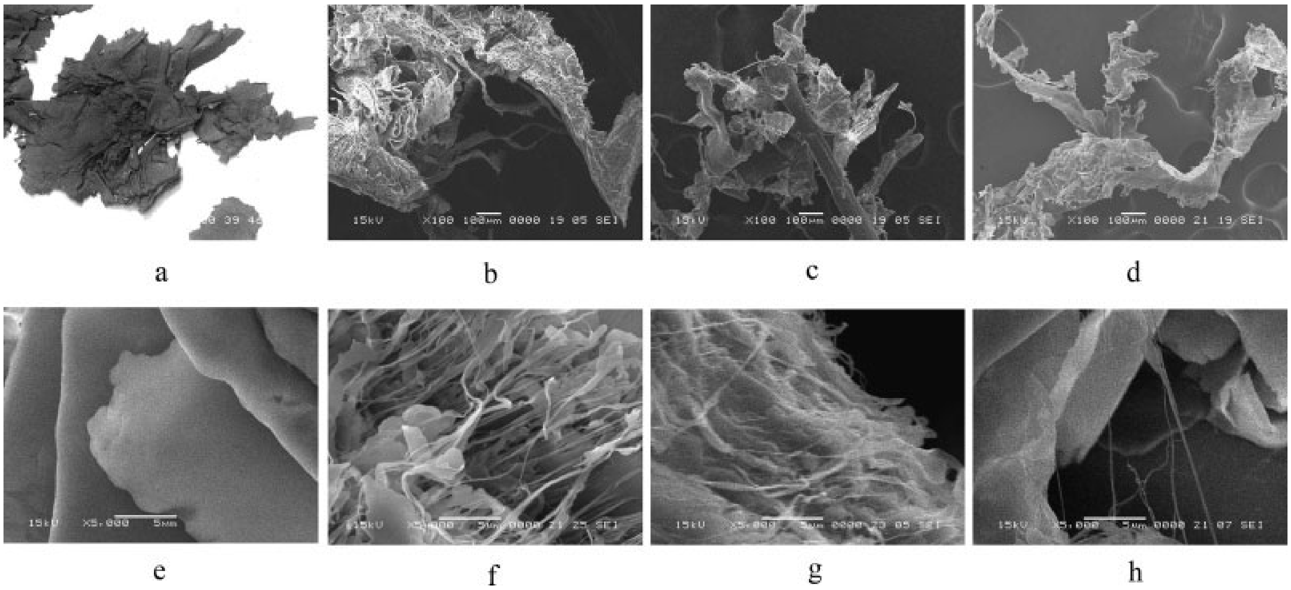


Figure 8 SEM images of debris for undrawn and drawn PTFE [(a) and (e): undrawn; (b) and (f): P direction; (c) and (g): AP direction; (d) and (h): N direction; (a–d): low magnification; (e–h): high magnification].

of drawn PTFE (Fig. 4), it is rational to deduce that the fibril structure of debris is closely related to the fiber structure of drawn PTFE. This indicates that the fiber structure formed by drawing can restrain formation of large flake-like debris, which effectively reduces the wear of drawn PTFE.

The friction coefficient and wear rate of drawn PTFE are strongly dependent on the oriented direction. When sliding in P direction, the shear force is parallel with the oriented fibrils formed by drawing and a smoothing worn surface is easily formed, which results in low friction coefficient. The fibril prevents the debris breaking away from bulk and decreases the wear breakage unit, which contributes to reducing the wear rate of drawn PTFE. For AP direction, the shear force is perpendicular to the oriented fibrils but also lying in the draw plane. For N direction, the oriented fibril end could be sheared. The shear force, in both AP and N direction, is higher than that in P direction,[12] which results in high friction coefficient and wear rate.

CONCLUSIONS

The friction coefficient and wear rate of drawn PTFE were strongly dependent on sliding directions. The higher the orientation degree was, the smaller the friction coefficient and the wear rate were. This is especially so at the draw ratio of seven in P direction. The anisotropy of tribological properties for drawn PTFE attributed to the bulk orientation structures of PTFE. The shear force in P direction is parallel with the oriented fibrils formed by drawing and a steady worn surface is easily produced, which results in the low friction coefficient. The fiber formed by drawing prevents the large flake-like debris from formation, which effectively reduces the wear rate of drawn PTFE.

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