

Effects of Solid Lubricants on Friction and Wear Behaviors of Polyamide 6

Li Du-Xin, Li Wen-Juan, Xie Ying, Li Xiang-Xiang

State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083, China

Received 18 July 2010; accepted 1 August 2011

DOI 10.1002/app.35409

Published online 29 November 2011 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: As solid lubricants, Polytetrafluoroethylene (PTFE), graphite, and ultra-high molecular weight polyethylene (UHMWPE) can improve the tribological properties of PA6. The mechanical and the tribological properties of polyamide 6 (PA6) composites filled with solid lubricants were researched. The blended materials were injection molded to provide the test samples. Mechanical properties were studied in terms of the tensile strength and impact strength. Friction and wear experiments were run at a rotating speed of 1500 rpm and under loads of 40 and 160 N. The worn surfaces were examined using a scanning electron microscope. It was found that an improvement of tribological properties can be obtained by preparing PA6 composites, which was closely related to the varieties and

the contents of solid lubricants added. At a load of 40 N, PTFE was the most effective to have reductions of both coefficient and mass wear rate, while at a load of 160 N, UHMWPE was the most helpful. The effects of Combination Solid Lubricants were also discussed. The results showed that synergistic reaction can be gained to modify the tribology capabilities of PA6. Moreover, the micrographs taken in the worn surface of PA6 composites revealed that adhesive wear, abrasive wear and fatigue wear occurred in this study. © 2011 Wiley Periodicals, Inc. *J Appl Polym Sci* 124: 4239–4248, 2012

Key words: solid lubricants; polyamide 6; mechanical; tribological properties

INTRODUCTION

Polyamide 6 (PA6), as the one in the family of engineering plastics, has the advantages of high strength, excellent corrosion resistance, suitable wear resistance, and favorable self-lubricating property. The extraordinary characteristics have greatly attracted researchers' attention to its application in the fields of sliding materials. However, the existence of abundant acylamino groups in the material results in some defects, such as strong water-absorptivity, instability of structural sizes, highly shrinkage.¹ There are still some problems to be resolved for pure PA6 as a kind of sliding materials, such as a higher coefficient of friction (COF) under dry conditions, a higher COF and wear rate and the worse friction stability under high load condition, and so on. Thus, further improvement is still required to meet more demanding applications.

To obtain better friction and wear properties, there are numerous studies on the performance of PA6 reinforced and modified by other fillers. Li et al.^{2,3} studied the effect of carbon fiber content on friction

and wear properties of carbon fiber reinforced PA6 composites. It was found that all filled PA6 had superior tribological characteristics comparing to unfilled. The optimum wear reduction was obtained when the CF content is 20 vol %. Meng et al.⁴ investigated the friction and wear behaviors of carbon nanotubes (CNTs) reinforced PA6 composites under dry sliding and water lubricated condition. The results showed that CNTs could improve the wear resistance and reduce the friction coefficient of PA6 considerably under both sliding conditions. The composites exhibited lower friction coefficient and higher wear rate under water-lubricated condition than under dry sliding. Zhao et al.⁵ reported the tribological performance of nano- Al_2O_3 reinforced PA6 composites. It was found that nano- Al_2O_3 improved the wear resistance of monomer casting PA6 with the optimal content of nano- Al_2O_3 being ~ 3 wt %.

It is well known that filling solid lubricants into polymers is an attractive option to obtain good friction and wear properties. There are significant efforts dedicated to the research and development of such solid lubricants as polytetrafluoroethylene (PTFE),^{6–10} graphite^{10–12} and ultra-high molecular weight polyethylene (UHMWPE),^{13,14} and others. In earlier articles, the tribological properties of polymers filled with these solid lubricants have been reported, such as PEEK,^{8,15} POM,^{16,17} PPS,^{10,18} and so on. They have superior friction and wear properties relative to those unfilled variants.

Correspondence to: L. Du-Xin (liduxin6404@yahoo.com).

Contract grant sponsor: Foundation of State Key Laboratory of Powder Metallurgy and Innovation Foundation of Central South University; contract grant number: LB09070.

Therefore, solid lubricants could be expected to significantly improve the friction and wear properties of PA6. In fact, some limited studies investigating the effects of solid lubricants on the performance of PA6 have been made in terms of mechanical properties, rheological behaviors, and so on. But the research for tribological properties is rarely found in the literatures. The purposes of this article are to clarify the effects of solid lubricants on the friction and wear behaviors of PA6, so as to provide some practical guidance for the use of PA6 composites.

EXPERIMENTAL

Materials and specimens

PA6 used in this experiment was purchased from the Shenzhen Changtai Plastic (Shenzhen, China). The PTFE (AGrade) used was supplied by the Tangshan Rifeng Chemical (Tangshan, China). The graphite (with a particle size of 25 μm) was purchased from the Shanghai Yifan graphite (Shanghai, China). The UHMWPE was purchased from the Shanxi zhongke TianGang Technology Development (Lvliang, China).

Preparation process

Before blending, PA6 was dried at 100°C for 6 h to remove most of absorbed humidity. The PA6 composites were prepared by the twin-screw extruder. The temperatures maintained in nine zones of the extruder barrel were 210, 220, 230, 240, 240, 240, 240, and 240°C. The screw frequency and the feeding frequency were set at 360 Hz and 20 Hz, respectively. The extrudate was obtained in the form of a cylindrical rod, which was cooled in water and then pelletized. To ensure steady-state operation and to flush impurities out of the system before getting the polyblends samples, the initial 1 kg of the extrudate was discarded.

Later, they are dried again and then the injection molding technique was applied to prepare the specimens, and the injection pressure was 45 MPa. The temperatures in four zones were 250, 250, 250, and 250°C and in the nozzle 230°C. The molded specimens were visually inspected for air bubbles and those with defects were discarded.

Property measurement

Tensile properties

The PA6 composites were cut into narrow-waisted dumbbell-shaped specimens in accordance with the Chinese standard GB/T1040-2006. The uniaxial tensile experiments were carried out on a CMT-7205 Universal Electronic Test Machine at room temperature. The tensile rate was 5 mm/min. For a more

accurate determination of the material parameters and consideration of the possible scatter in the experimental data, five specimens with the same composition were tested in each group. The obtained quantities were then averaged.

Impact strength

The impact fracture tests of the simple beams with "U" notch at one side of specimen were implemented on a JB-S Impact Test Machine at room temperature in accordance with the Chinese standard GB/T1043-93. The size of notch is 3.50 \times 10.36 mm². No less than five specimens were measured in each group.

Friction and wear tests

Friction and wear tests were done using a reciprocating UMT-3 tribometer at room temperature under dry friction condition. The specimens (25 mm in length, 25 mm in width, and 10 mm in thickness) were cleaned by ultrasonic washer before testing. The tests were conducted at loads of 160 and 40 N. The test duration was 2 h and the rotational speed was set at 1500 rpm.

Weight loss measurements were made using an analytical balance having an accuracy count of 10⁻⁴ g. Specific wear rate was calculated using the following equation:

$$\text{Wear rate} = \frac{\Delta m}{\rho L d} \text{cm}^3 \text{N}^{-1} \text{m}^{-1}$$

where Δm is the mass loss in grams, ρ is the density of the test material in g cm⁻³, L is the load in Newton, and d is the sliding distance in meters.

Scanning electron microscope (SEM) observation

After the friction and wear tests, the cleaned samples were allowed to dry. Before the scanning electron microscope (SEM) observation, the worn surfaces of PA6 composites were coated with a thin layer of gold, and then were observed under JSM-6363LV SEM.

RESULTS AND DISCUSSION

Effects of PTFE on the properties of PA6

The mechanical properties of PA6 composites with PTFE content are shown in Figure 1. After being filled with PTFE, it can be observed that the tensile strength and impact strength of PA6 composites were improved compared with pure PA6. With increasing content of PTFE, the tensile strength increased first, then decreased. A peak appeared when the additive

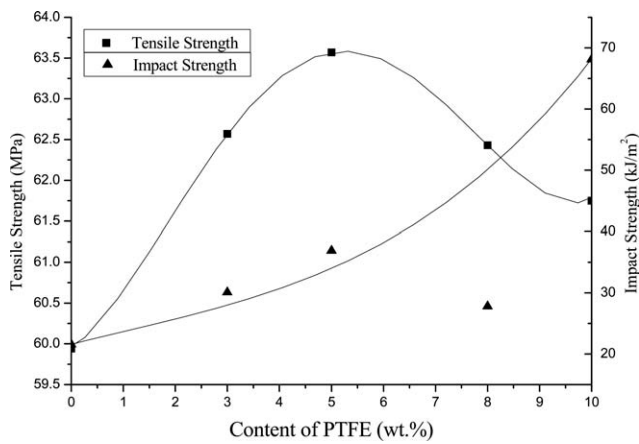


Figure 1 Mechanical properties of PA6 filled with PTFE.

amount was 5 wt %. A possible explanation is the interface bonding between PA6 and PTFE became weak when the addition of PTFE increased over 5 wt %. Compared with pure PA6, there was a dramatic increase in the impact strength after addition of PTFE. It is mainly attributed to that PTFE with good ductility could absorb more energy in impact test. Yet, adding 8 wt % PTFE did not keep the trend of continuously rising. The possible reason is the existence of defects and impurities in materials, which resulted in the discontinuity of impact properties.

PTFE is one of the generally used solid lubricants that could reduce the COF, and, due to this fact, sometimes the wear rate of polymeric composites. Figure 2 shows that the COF and wear rate of the composites decreased relative to pure PA6, and the decreasing tendencies obviously differed with the loads applied. For the COF, the addition of 8 wt % PTFE was the most effective at a load of 40 N, while 10 wt % PTFE at a load of 160 N. As it is known that PTFE exhibits very low COF, and adding PTFE into polymers can obtain composites with

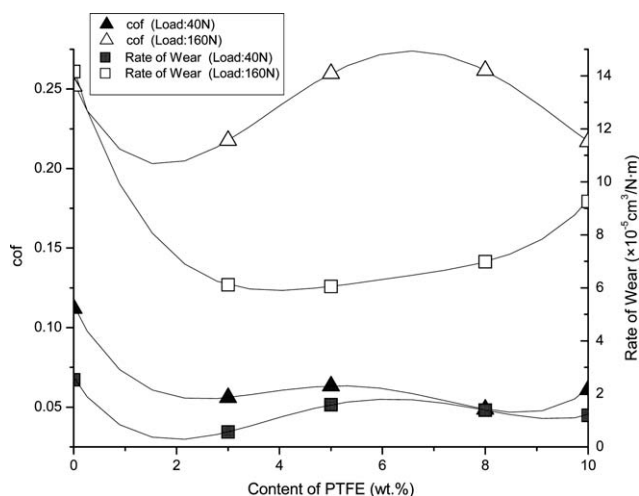


Figure 2 Variation of friction and wear behaviors of PA6 composites with PTFE content.

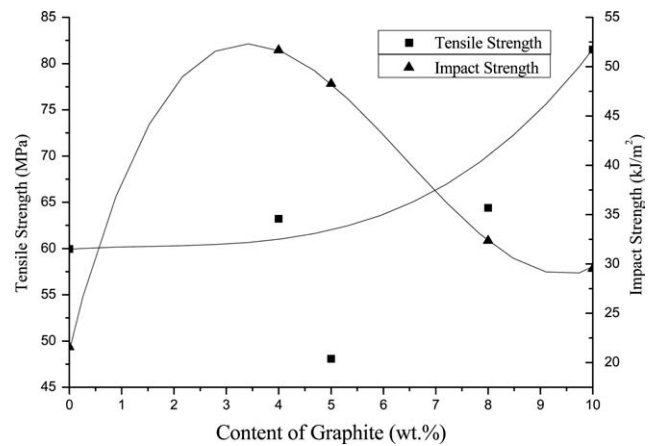


Figure 3 Mechanical properties of PA6 filled with graphite.

the lower COF. Furthermore, PTFE can be easily dragged out from the matrix to form a third-body transfer film, which reduces the direct contact between matrix and counterpart.¹⁹ The emergence of the transfer film can give a further reduction for the COF. The abrasive resistance of PA6 composites was improved obviously after adding PTFE. To be specific, 3 and 5 wt % PTFE filled PA6 composite exhibited the lowest mass wear rate at loads of 40 and 160 N, respectively. This result is closely related to the transfer film formation on the counterpart material. With the increase of PTFE, the transfer film is completed gradually. But PTFE itself has a relatively low wear resistance due to its soft nature. So excessive PTFE content is not profitable for the wear resistance. In addition, the mass wear rate was associated with the strength of the materials.

It can be seen that the COF and wear rate of the composites increased with the increasing of load in Figure 2. It can be illustrated by the increasing area of contact between the metal counterpart and the composites which induced more serious adhesion and deformation, and as a result, the COF increased. At the same time, the increasing of applied load promoted a temperature rise hence, softening the polymer surface, speeding up the generation of viscous layer, breaking the uniformity of transfer film, which resulted in an increase of the wear rate.

The above experimental results reveal that PTFE greatly improves the friction and wear properties of PA6 composites, especially at a lower load. The modification effect depends largely on the efficiency of creating a lubricating transfer film of PTFE on the steel counter surface. With the increase of the load, the COF and mass wear rate increase.

Effects of graphite on the properties of PA6

Figure 3 shows the mechanical properties of PA6 filled with graphite. It can be seen that the effects of

TABLE I
Coefficient of Friction and Wear Rate of Graphite/PA6 Composites Under Different Loads

Samples	Coefficient of friction		Wear rate ($\times 10^{-5}$ cm ³ N ⁻¹ m ⁻¹)	
	40 N	160 N	40 N	160 N
PA6	0.1121	0.2517	2.5346	14.159
PA6 + 4% graphite	0.1621	0.3833	9.5293	10.757
PA6 + 5% graphite	0.1512	0.4680	6.3849	9.8941
PA6 + 8% graphite	0.2383	0.5707	8.3275	15.182
PA6 + 10% graphite	0.1198	0.2690	4.3482	7.4458

graphite on the different performance of PA6 were in no agreement. With the addition of the graphite into PA6, the tensile strength can be improved with the exception of 5 wt %. It is mainly attributed to the presence of graphite particles, which can make the crystal structure more fine and homogeneous. Consequently, the stretch-proof capacities of PA6 composites enhanced. The decrease at 5 wt % graphite content may be due to the heterogeneous mixture in the process of material preparation. With increasing content of graphite, the impact strength increased first, then decreased. The maximum value emerged when the additive amount was 4 wt %. A small amount of graphite particles played a part of rigid fillers to improve the impact strength of PA6 composites. Nevertheless, an excess of graphite addition would divide the resin structure, which induced stress concentration and the decrease of effective cross sectional area bearing pressure. As a result, the impact strength decreased.

Table I shows the data of the COF and wear rate of the Graphite/PA6 composites under both loads. As one of the three forms of carbon, graphite has a layer structure (carbon layer) in which the atoms are arranged in a hexagonal unit cell within each layer.^{20–22} These layers are linked by weak Van der Waals bonds, which may be easily broken by shear

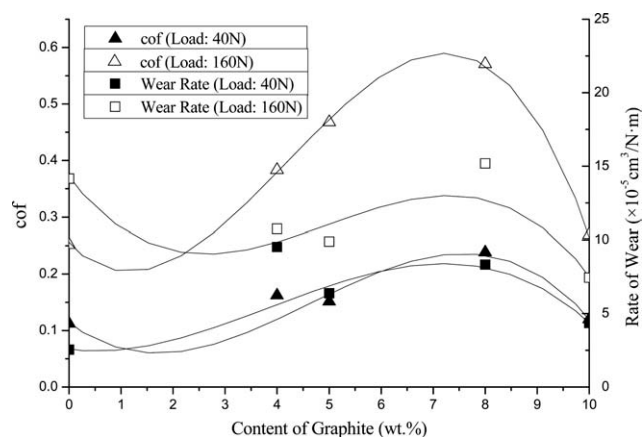


Figure 4 Variation of friction and wear behaviors of PA6 composites with graphite content.

forces under sliding conditions. Therefore, graphite is also a potential candidate of fillers, which could form a transfer film on the sliding counterpart. The COF and wear rate of PA6 filled with various amounts on graphite are shown in Figure 4. When the content of graphite increased from 4 to 10 wt %, the COF did not decrease as we predicted at loads of 40 and 160 N. The possible reason is that the inclusion of graphite softened the composites, which enlarged the actual contact area. In accordance with simple adhesion theory of Bowden, the frictional force is in proportion to the actual contact area. Consequently, the COF increased. As for the mass wear rate, it demonstrated a regular pattern similarly to the variation of COF when a load of 40 N was applied. By comparison, the wear rate of the PA6 composites decreased gradually with addition of graphite at a higher load of 160 N. In addition, the 10 wt % graphite contributed to an most obvious improvement of abrasive resistance. Therefore, it could be inferred that graphite dragged out from the matrix more easily to form a continuous and smooth transfer film at a higher load.

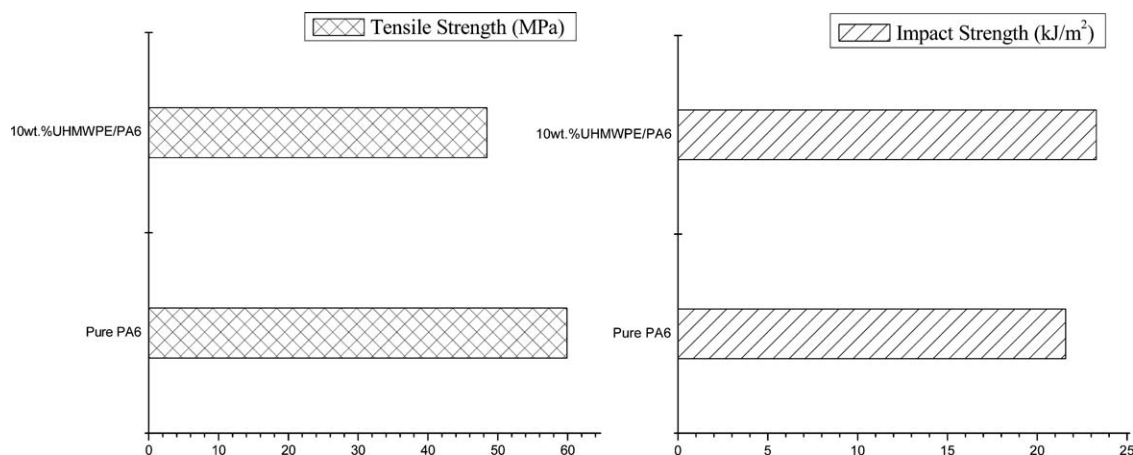


Figure 5 Mechanical properties of PA6 filled with UHMWPE.

TABLE II
Coefficient of Friction and Wear Rate of UHMWPE/PA6 Composites Under Different Loads

Samples	Coefficient of friction		Wear rate ($\times 10^{-5}$ cm ³ N ⁻¹ m ⁻¹)	
	40 N	160 N	40 N	160 N
PA6	0.1121	0.2517	2.5346	14.159
PA6 + 10% UHMWPE	0.09273	0.07407	1.3155	3.1046

The variation of the COF and wear rate of graphite-filled composites under different loads was similar to that of the PTFE filled composites. With the load increasing, the COF and wear rate increased.

The experimental results demonstrate that graphite was better suited to modify the friction and wear properties of PA6 at a higher load. At a load of 40 N, neither a reduction of the COF nor a reduction of the mass wear rate did occur. By comparison, the abrasive resistance of materials filled with graphite was improved at a load of 160 N. Meanwhile, the tribological properties of the composites decreased with increasing of load.

Effects of UHMWPE on the properties of PA6

UHMWPE possesses excellent self-lubrication properties, high impact resistance, and high chemical stability, which make it widely used in engineering applications, such as bearing materials, sliding wear, and corrosive environment.²³ Thus, we tried to enhance the tribological properties of PA6 composites by adding UHMWPE. The additive amount of 10 wt % was selected to compare the modification results with other solid lubricants. Figure 5 illustrates the mechanical properties of PA6 filled with 10 wt % UHMWPE. It can be observed that the impact behavior was improved, while the other deteriorated. For the thermodynamic incompatibility between PA6 and UHMWPE, the additive UHMWPE could not

disperse homogeneously in the matrix, which induced the weak bonding strength on the interface of the blend. Thus the tensile strength of the blends was not improved. However, UHMWPE in the composites turned into stress concentrating points and resulted in the emergence of craze when the materials suffered shock, which could absorb more impact energy. Therefore, the impact strength was increased.

Table II shows the data of the COF and wear rate of the UHMWPE/PA6 composites under both loads. It is deserved to be mentioned that UHMWPE proved to be very effective in friction and wear tests. Figure 6 demonstrates that UHMWPE made a obvious reduction of both the COF and the mass wear rate at a load of 40 and 160 N. The improvement of the tribology capabilities is due to that non-polar UHMWPE has a smooth molecular chain structure, so it can form a boundary layer with low shear strength.

Unlike the variation of friction and wear behaviors with load above, the COF of 10 wt % UHMWPE filled PA6 composite was lower at a higher load of 160 N. The possible explanation is along with the load increasing, the accumulation of friction heat made the temperature of friction surface easily reach to softening point or melting point. In addition, the COF was connected with the surface layer flowing of materials caused by softening, melting, reorientation, and so on.

Although the exploration of UHMWPE as a solid lubricant is only preliminary, it has showed its advantages of modifying the tribological properties of PA6 composites, especially at a higher load. Its superior lubricating property is remarkable.

Comparative study on the improved effects of solid lubricants

The tribological behaviors of the composites of PA6 modified by PTFE, graphite, and UHMWPE were

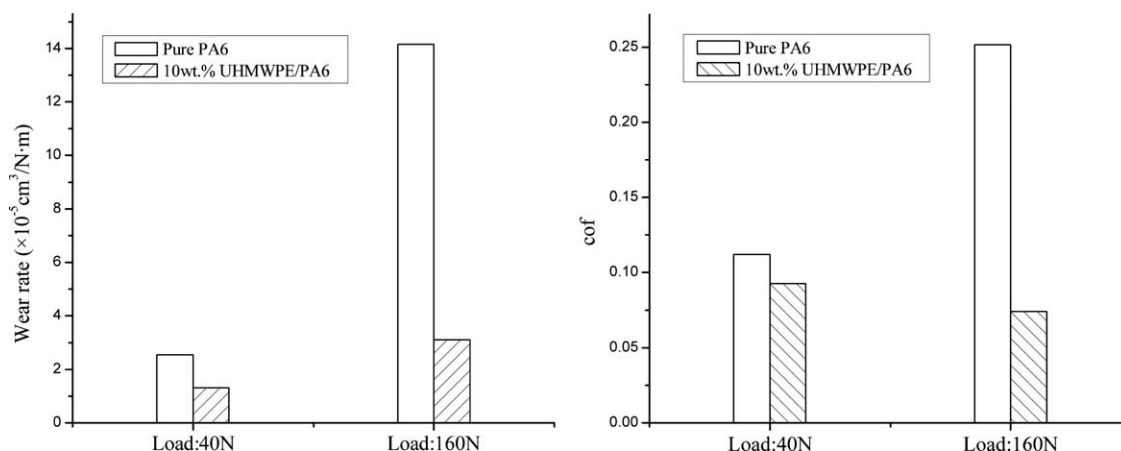


Figure 6 Effects of UHMWPE on friction and wear behaviors of PA6.

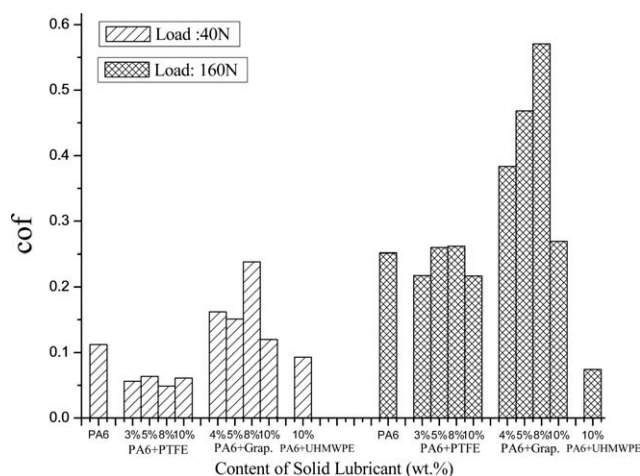


Figure 7 Variation of COF with solid lubricants.

investigated above. In this section, the modification effects of solid lubricants used in our experiment were compared. In Figure 7, the effects of solid lubricants on decreasing the COF are studied. At a load of 40 N, the composites filled with PTFE exhibited a lower COF than the others did. With the optimal fill amount of 8 wt %, the COF was lowered by 56.6% compared to pure PA6. Second, UHMWPE was also effective, and PA6 filled with 10 wt % UHMWPE had a reduction of 17.3%. Third, the COF of PA6 composites did not decrease with the content of graphite. When the applied load increased to 160 N, UHMWPE turned out to be the most suitable. The addition of 10 wt % made a reduction of 70.6%. PTFE appeared to be weak to lower the COF, obtaining 13.8% reduction only when the content increased to 10 wt %. Graphite still had no positive effect on lowering the COF.

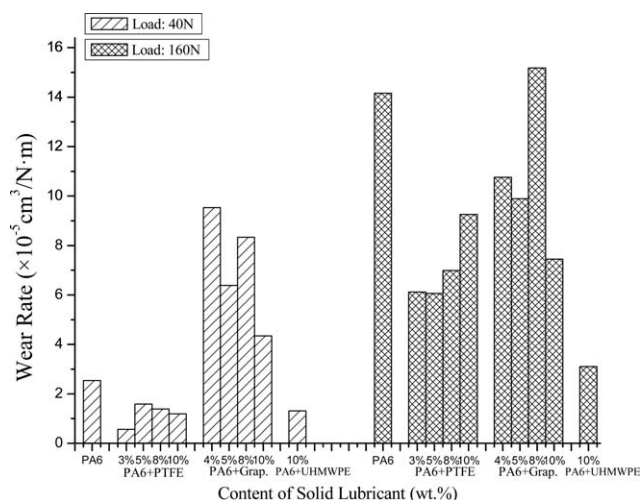


Figure 8 Variation of wear rate with solid lubricants.

The influences of three solid lubricants on the wear rate of PA6 composites were similar to the former, as indicated in Figure 8. The comparison reveals that the inclusion of PTFE made the materials achieve the best wear resistance at a load of 40 N. With the optimal fill amount of 3 wt %, 77.7% decreasing of wear rate occurred. Besides, when 10 wt % UHMWPE was added, there was a 48.1% decrease. In the case of graphite, it made the wear rate all the larger. At a load of 160 N, the addition of each solid lubricant made an improvement of wear resistance. For the modification effects of three solid lubricants, UHMWPE was the best, PTFE second best, and graphite third best. In detail, the optimal wear resistances were acquired with 5 wt % PTFE, 10 wt % graphite, and 10 wt % UHMWPE, and the decreased percentages were 57.2, 47.4, and 78.1%, respectively.

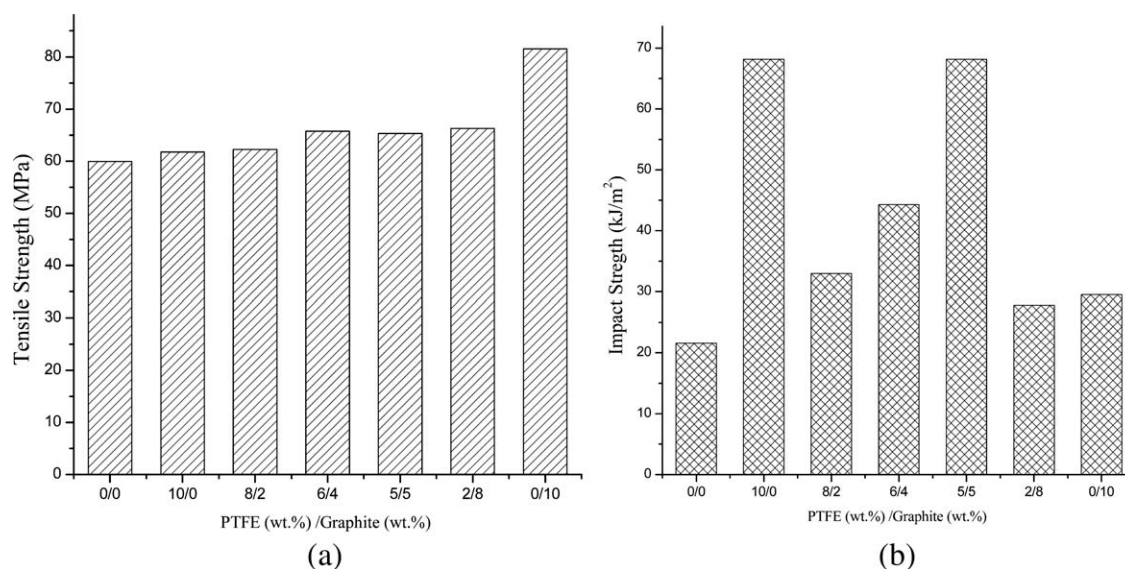


Figure 9 Mechanical properties of PA6 filled with combination solid lubricants.

TABLE III
Coefficient of Friction and Wear Rate of PTFE/Graphite/PA6 Composites Under Different Loads

Samples	Coefficient of friction		Wear rate ($\times 10^{-5}$ cm ³ /N m)	
	40 N	160 N	40 N	160 N
PA6	0.1121	0.2517	2.5346	14.159
PA6 + 8% PTFE + 2% graphite	0.05989	0.2167	1.1665	9.3781
PA6 + 6% PTFE + 4% graphite	0.06112	0.3176	0.76772	1.7062
PA6 + 5% PTFE + 5% graphite	0.06377	0.2396	1.1587	12.326
PA6 + 2% PTFE + 8% graphite	0.1331	0.3840	4.4251	12.071

In conclusion, the modification effects of three solid lubricants are dependent on the amounts and the loads applied. PTFE exhibited excellent lubricity at a lower load, while UHMWPE at a higher load.

Effects of combination solid lubricants on the properties of PA6

Analysis, the influences of three solid lubricants on the properties of PA6 composites, points out that they have their own roles in different aspects. In an effort to make further improvements in the tribological behaviors of PA6 composites, another possible approach was tried. That was the application of combination solid lubricant. In this article, it referred to that, PA6 was filled with combination solid lubricants, which were composed of various proportions of PTFE and graphite. The results of this approach are given below.

Figure 9 shows the mechanical properties of PA6 filled with Combination Solid Lubricants. Firstly, it can be noted that the addition of 10 wt % solid lubricants with different proportions increased the

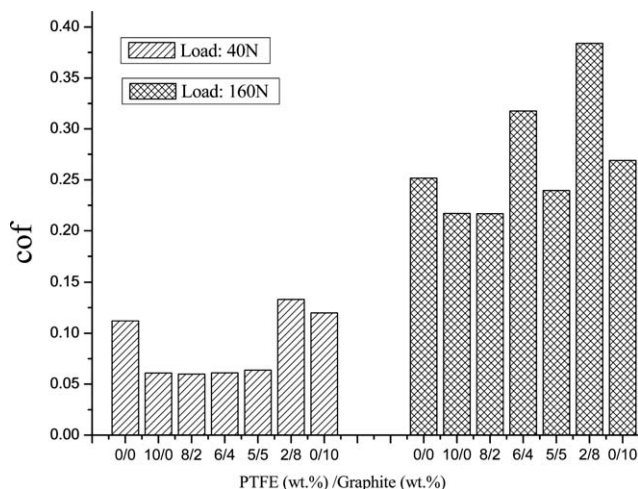


Figure 10 Variation of COF of PA6 composites with the proportion of combination solid lubricants.

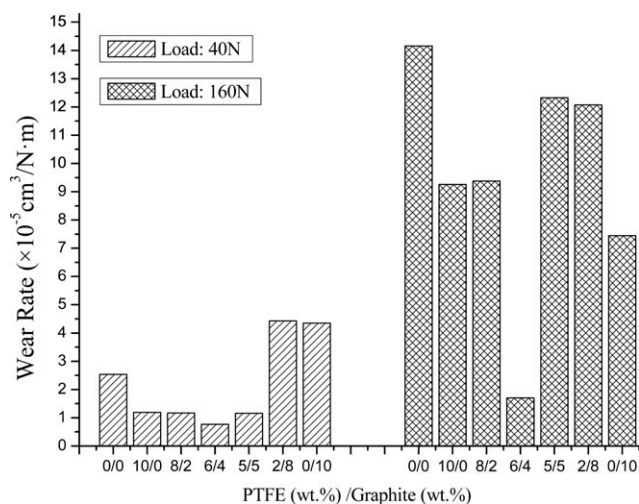


Figure 11 Variation of wear rate of PA6 composites with the proportion of combination solid lubricants.

tensile strength of PA6. It is also noted that with increasing graphite content, the tensile strength increased when the content of solid lubricants had a fixed and unchanging value of 10 wt %. Therefore, we can infer a conclusion from the facts that graphite was more effective to improve the tensile strength. Secondly, PTFE and graphite were helpful to improve the impact strength. Furthermore, there was a maximum when the proportion was 5 wt % PTFE–5 wt % Graphite than others. It was suspected that synergistic reaction existed in the use of combination solid lubricants.

Table III shows the data of the COF and wear rate of the PTFE/Graphite/PA6 composites under both loads. Figure 10 shows the variation of COF of PA6 composites with the proportion of combination solid lubricants. At a load of 40 N, as the proportion of PTFE increased, the COF decreased. There was a largest reduction when PA6 was filled with 8 wt % PTFE–2 wt % Graphite. When the load increased to 160 N, the most obvious reduction of COF also appeared with the proportion of 8 wt % PTFE–2 wt % Graphite. In addition, the COF of the composite was even lower than that with 10 wt % PTFE added. Thus, the combination solid lubricants could decrease the COF of PA6 composites more significantly, compared with the addition of a single solid lubricant.

The variation of wear rate of PA6 composites with the proportion of combination solid lubricants is presented in Figure 11. Compared with pure PA6, it is found that the composites with combination solid lubricants acquired a lower wear rate regardless of the load applied, except that with 2 wt % PTFE–8 wt % Graphite at a load of 40 N. The wear rate of the materials filled with 6 wt % PTFE–4 wt % Graphite was the lowest at loads of 40 and 160 N, and it was also lower than that filled with a single composition.

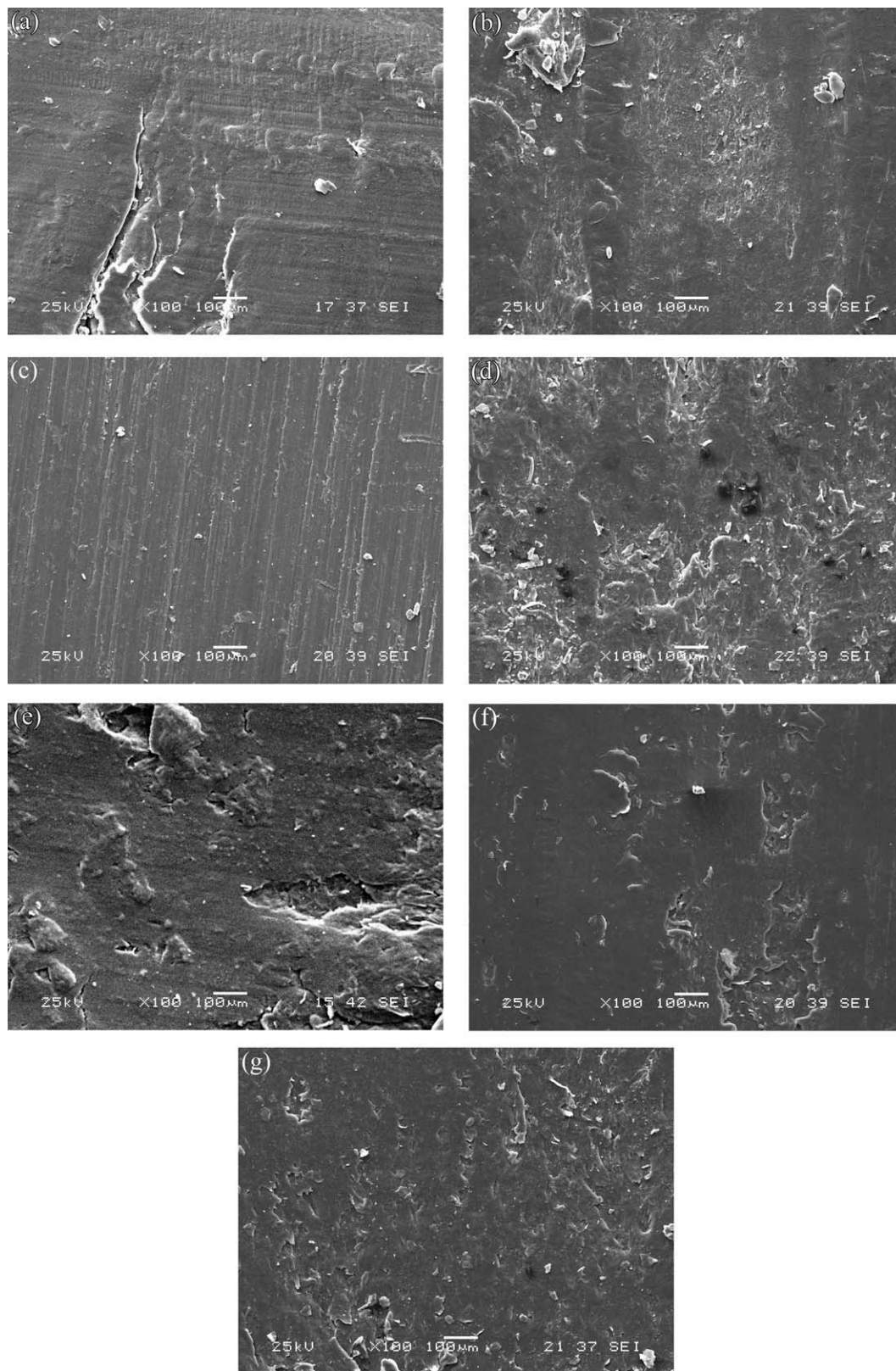


Figure 12 SEM image of worn surfaces of PA6 composites (load: 40 N): (a) Neat PA6, (b) PA6 + 3 wt % PTFE, (c) PA6 + 8 wt % PTFE, (d) PA6 + 4 wt % graphite, (e) PA6 + 10 wt % graphite, (f) PA6 + 5 wt % PTFE + 5 wt % graphite, and (g) PA6 + 2 wt % PTFE + 8 wt % graphite.

In conclusion, with the appropriate proportion of the Combination Solid Lubricants, synergistic reaction can be gained to modify the tribology capabilities of PA6 composites.

SEM studies on worn surfaces

According to the generally accepted models of material wear,²⁴ three mechanisms contribute to the wear processes of PA6 composites, which are adhesive wear, abrasive wear, fatigue wear respectively. Their relative contribution depends on the load level as well as on the chemical, mechanical and geometrical properties, and lubricating conditions.

To understand the effects of solid lubricants on the wear behaviors of PA6, the worn surfaces of the materials tested under 40 N were studied by SEM, as shown in Figure 12.

In the case of neat PA6 [Fig. 12(a)], the surface showed deep rill-like folds caused by adhesion. Thus, it can be concluded that adhesive wear was the main wear mechanism. For the unfilled PA6, severe adhesive wear is attributed to the softening of PA6, which is due to the increased temperature at two frictional surfaces.

Contrary to the above, there existed lamellar structure among the appearance of the worn surface of PA6 with 3 wt % PTFE [Fig. 12(b)], which was a result of plastic deformation. So the main wear mechanism was adhesive wear. When the proportion of PTFE was 8 wt %, there was parallel and regular ploughing ditch on the worn surface [Fig. 12(c)]. PTFE has been reported to form a molecularly smooth transfer film in earlier studies.²⁵ When sliding against steel surface, a preferential transfer of PTFE to the counterface occurred. The formation of a thin and uniform PTFE transfer layer decreased the contact and adhesion between the polymer and the metal surface, decreasing the wear loss consequently. The ploughing ditch and abrasive dust embedded shows that significant abrasive wear occurred. That means that the matrix far from the PTFE has the same wear mechanism with neat PA6. When the content of PTFE is over a certain value, the wear mechanism is different.

As for PA6 composites with graphite content, the worn surfaces differed from those with PTFE content. When sliding against a steel counterface, the tiny graphite particles in the PA6 matrix played a role of a lubricating agent. The bond between graphite and PA6 may prevent graphite particles from being easily transferred onto the surface of counterface. With the addition of 4 wt % graphite, it can be seen that there were graphite particles on the worn surface in Figure 12(d). At the same time, it was also noted that the surface was not quite smooth and appeared to have some lamellar structure shaped in

the form of islands, which might be caused by adhesive wear. Whereas, the surface had peeled off extensively, and even microcracks emerged when the content of graphite increased to 10 wt %, as seen in Figure 12(e). Fatigue wear was proved to generate.

Large sections of removal as seen here is not observed in the case of PA6 composites with 5 wt % PTFE–5 wt % graphite, as seen in Figure 12(f). The worn surface was relatively smooth and the peeling was constrained due to the combination of PTFE and graphite. As a comparison, the proportion influenced the wear process in a way. In Figure 12(g), severe wear was observed on the worn surface of the composites with 2 wt % PTFE–8 wt % graphite. The wear loss is relevant to the strength of materials. The strength of PA6 composite with 2 wt % PTFE–8 wt % graphite was lower than that with 5 wt % PTFE–5 wt % graphite. Furthermore, its COF was larger. Thus, the attrition was intensified. PA6 composites with 2 wt % PTFE–8 wt % graphite presented the feature of adhesive wear.

CONCLUSIONS

The following conclusions can be drawn from this study.

1. At a load of 40 N, the PA6 composites modified with PTFE exhibited the excellent friction and wear properties. Compared with pure PA6, the inclusion of 8 wt % PTFE resulted in a 56.6% reduction of the COF, and the inclusion of 3 wt % PTFE resulted in a 77.7% reduction of the wear rate.
2. At a load of 160 N, UHMWPE was the most effective solid lubricant to improve the tribological behaviors of PA6. With the addition of 10 wt % UHMWPE, there was a 70.6% reduction of the COF, and a 57.2% reduction of the wear rate.
3. With the applied load increasing, the friction and wear properties of PA6 composites showed a descending tendency.
4. With the application of Combination Solid Lubricants, synergistic reaction can be gained to modify the tribology capabilities of PA6. Hence, it is worth to make further efforts.
5. The tribological mechanism of PA6 was closely related to the varieties and the contents of solid lubricants added. The micrographs taken in the worn surface of PA6 composites reveal that adhesive wear, abrasive wear, and fatigue wear occurred in this study.

References

1. Zhao, R. G.; Luo, W. B.; Xiao, H. M.; Wu, G. Z. *Trans Nonferrous Metals Soc China* 2006, 16, 498.

2. Nie, W. Z.; Li, J. *Plast Rubber Compos* 2010, 39, 10.
3. Li, J.; Xia, Y. C. *Polym Compos* 2010, 31, 536.
4. Meng, H.; Sui, G. X.; Xie, G. Y.; Yang, R. *Compos Sci Technol* 2009, 69, 606.
5. Zhao, L. X.; Zheng, L. Y.; Zhao, S. G. *Mater Lett* 2006, 60, 2590.
6. Sun, L. H.; Yang, Z. G.; Li, X. H. *Polym Eng Sci* 2008, 48, 1824.
7. Bijwe, J.; Naidu, V.; Bhatnagar, N.; Fahim, M. *Tribol Lett* 2006, 21, 59.
8. Jia, J.; Chen, J.; Zhou, H.; Hu, L. *Tribol Lett* 2004, 17, 231.
9. Bijwe, J.; Sen, S.; Ghosh, A. *Wear* 2005, 258, 1536.
10. Yu, L. G.; Yang, S. R.; Liu, W. M.; Xue, Q. J. *Polym Eng Sci* 2000, 40, 1825.
11. Shan, K. L.; Xiang, D. H. *Optoelectron Adv Mater Rapid Commun* 2007, 1, 648.
12. Zhan, G.; Rashevaa, Z.; Schlarbb, A. K. *Wear* 2010, 268, 893.
13. Hashmi, S. A. R.; Neogi, S.; Pandey, A. *Wear* 2001, 247, 9.
14. Liu, C. Z.; Ren, L. Q.; Tong, J.; Joyce, T. J.; Green, S. M.; Arnell, R. D. *Wear* 2001, 249, 31.
15. Burris, D. L.; Sawyer, W. G. *Wear* 2006, 261, 410.
16. Benabdallah, H. *Wear* 2003, 254, 1239.
17. Sun, L. H.; Yang, Z. G.; Li, X. H. *Polym Eng Sci* 2008, 48, 1824.
18. Chen, Z. B.; Liu, X. J.; Li, T. S.; Lu, R. G. *J Appl Polym Sci* 2006, 101, 969.
19. Friedrich, K.; Pipes, R. B. *Friction and wear of polymer composites*; Elsevier: The Netherlands, 1986.
20. Kang, S. C.; Chung, D. W. *Wear* 2003, 254, 1.
21. Myshkin, N. K.; Petrokovets, M. I.; Kovalev, A. V. *Tribology Int* 2005, 38, 11.
22. Briscoe, B. J.; Yao, L.; Stolarski, T. A. *Wear* 1986, 108, 4.
23. Liu, C. Z.; Wu, J. Q.; Li, J. Q.; Ren, L. Q.; Tong, J.; Arnell, A. D. *Wear* 2006, 260, 109.
24. Wen, S. Z.; Huang, P. *Tribology Principle*; Tsinghua University Press: Beijing, 2002.
25. Palabiyik, M.; Bahadur, S. *Wear* 2002, 253, 369.