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Statistical wear analysis of PA-6/UHMWPE alloy, UHMWPE and PA-6

C.Z. Liu [a,*], L.Q. Ren [b], J. Tong [b], T.J. Joyce [a], S.M. Green [a], R.D. Arnell [c]

[a] *School of Engineering, University of Durham, Durham DH1 3LE, UK*
[b] *Centre for Bionic Research, Jilin University of Technology, 130025 Changchun, PR China*
[c] *Centre for Advanced Materials and Surface Engineering, University of Salford, Salford M5 4WT, UK*

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Abstract

This paper, based on an orthogonal experimental design and analysis method, reports the wear of a blend of polyamide-6/ultrahigh molecular weight polyethylene (PA-6/UHMWPE), using a pin-on-disc test, and rubbing against a stainless steel counterface. The wear behavior of PA-6 and UHMWPE was also investigated for the purpose of comparison. The main purpose was to study the influence of the parameters: sliding distance, contact pressure and sliding speed on the wear performance of the investigated materials. Statistical analysis was carried out to develop an equation in which the wear volume of the specimen was expressed in terms of sliding distance, contact pressure and sliding speed. It was observed that the wear rate was lower for PA-6 than the other two materials. UHMWPE exhibited the lowest wear resistance. Contact pressure was found to be the most important factor in the wear of materials, followed by sliding distance and sliding speed. Sliding distance had the highest relative effect on the wear of PA-6/UHMWPE. Sliding speed seemed to have the least effect on the wear volume of the investigated materials. The results show that the wear behavior of these materials, and the effects of factors on the wear, depend on the physical and mechanical properties of the materials. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Wear; Ultrahigh molecular weight polyethylene; Polyamide; Alloy

1. Introduction

Innovations in modern technology have placed every-increasing demands on advanced plastic materials. Polyamide-6 (PA-6) is an important polymer for engineering applications because of its excellent mechanical properties. But its sensitivity to notched impact and poor dimensional stability limit its application in a wet environment [1]. Ultra-high molecular weight polyethylene (UHMWPE) is another important polymer, it possesses excellent self-lubrication properties, it has excellent impact resistance and high chemical stability [2,3]. But its low deformation temperature and difficulty to mould, form a limitation to its applications [4]. The blend of PA-6/UHMWPE could overcome the shortcomings of both polymers while, at the same time, perhaps possessing the advantages of both polymers [5]. The proposed application of the PA-6/UHMWPE alloy was that of a cage for a roller bearing in a water pump and the wheel hub of an automobile. This application was considered to be a low load and high speed situation, hence the test conditions specified later.

Much research on the wear performance of PA-6 and UHMWPE has been done [6–10]. Yet much of the knowledge on the tribological behavior of UHMWPE and PA-6 is empirical and very limited predictive capability currently exists. Very little has been reported on the wear performance of PA-6/UHMWPE alloy. As a new material, a fundamental and comprehensive understanding of the wear performance of PA-6/UHMWPE alloy is required.

Although wear is an intrinsic material property, it also depends on operating parameters. A relationship between the wear of the investigated polymers and operating parameters is desirable in order to obtain a better understanding of the wear behavior. Rhee [11], Lancaster [12], Dowson et al. [13], Viswanath and Bellow [14] have developed various forms of equations/relationships for the wear of polymers. All these models have expressed wear volume as a function of either the operating parameters, such as load/contact pressure, speed, sliding distance, or include properties such as hardness and surface roughness of the counterface, shear strength of the polymer, etc. Most of the wear equations have related the volume loss to the operating parameters through a wear constant or a wear coefficient. However, such models do not describe the influence of the individual operating parameters and their interactions on the wear. It is important to know the effect of the individual

* Corresponding author. Tel.: +44-191-374-3827; fax: +44-191-374-2550.
E-mail address: chaozong.liu@durham.ac.uk (C.Z. Liu).

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factors and their interactions on the wear behavior of materials for the potential applications. Such information is expected to add to an understanding of polymer wear, optimize the use of existing materials and aid the development of new materials for service in such conditions.

In this paper, based on an orthogonal test design and analysis method, the wear performance of PA-6/UHMWPE alloy were studied using a pin-on-disc machine. The effects of contact pressure, sliding speed and sliding distance on the wear volume were investigated in order to assessing the wear performance of PA-6/UHMWPE. Efforts were made to correlate wear volume to contact pressure, sliding speed, and sliding distance. The results were compared with those of PA-6 and UHMWPE.

2. Experimental details

2.1. Materials and preparation

Starting materials: UHMWPE powder (M-3, MW $= 2.5 \times 10^6$), from BAA (Beijing); raw polyamide-6 (PA-6) pellets, from BASF; high density polyethylene grafted with 0.5% maleic anhydride (HDPE-g-MAH), as compatibilizer; were prepared in the laboratory. The alloy was prepared from 20% (by weight) of UHMWPE, 75% of PA-6, and 5% of HDPE-g-MAH compatibilizer. The alloy was prepared by melt mixing in a Berstorff ZE 25 × 43D co-rotating intermeshing twin screw extruder. The extrudates were quenched in a water bath, pelletized and dried at 80°C for 16 h, then fed into an extruder to inject into a mould to obtain the test specimens. The comparison materials were: commercial UHMWPE (MW $= 2.5 \times 10^6$) in the form of 25 mm diameter rod; and PA-6 in the form of 10 mm diameter rod. The test specimens were machined from these row rods. The properties of the three materials are listed in Table 1.

2.2. Pin-on-disc test

Wear tests were carried out on a computer controlled pin-on-disc wear test rig at room temperature under a water based lubricant (water/soluble oil = 95/5) conditions. The UHMWPE, PA-6 and PA-6/UHMWPE pin specimens, with a diameter of 5 mm, were machined from 10 mm diameter rod. Each test pin was notched at its upper end to provide good location and hence to prevent rotation, and was held within the specimen holder. The 316 stainless steel was used as the disc material, and the surface was ground with 1200 grit abrasive paper prior to the wear test. The disc was fitted on a turntable that was driven by a variable speed motor. Load was applied by a dead weight on the pin holder. The pin-on-disc test rig is shown in Fig. 1.

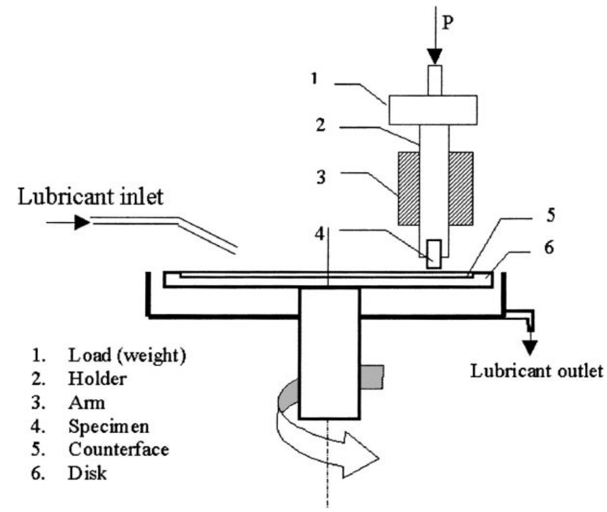

Fig. 1. Schematic diagram of pin-on-disc test rig.

Prior to the commencement of a test, the pins were dried in an oven at 80°C for 8 h and carefully weighed. After the test, the pins were also dried at 80°C for 8 h, then weighed using an analytical balance with a precision of ±0.1 mg. Wear of the test pin was defined as the weight loss with respect to the initial weight. The wear was expressed as the volume loss, y, in mm^3, which was calculated from the weight loss and the density of the specimen, i.e. y is the weight loss and g the density of the specimen (g mm^{-3}).

3. Results and discussion

3.1. The test arrangement and results

The effects of sliding distance (z_1, km), contact pressure (z_2, MPa), and sliding speed (z_3, m s^{-1}) on the wear volume loss were investigated. The investigated parameters and their test levels are listed in Table 2. The orthogonal array $L_9(3^4)$ was selected to arrange the test program, and each

Table 1
Physical and mechanical properties of specimens

Properties	UHMWPE	PA-6	PA-6/UHMWPE
Density (g mm^{-3})	0.935	1.13	1.06
Water absorbtion (%)	0.01	1.8	1.1
Elongation (%)	300	200	35
Melting point (°C)	141	235	224
Impact strength (kJ m^{-2})	Not break	7.8	12.7
Tensile strength (MPa)	41	56	51

Table 2
The investigated parameters and their test levels

Investigated parameters	Sliding distance z_1 (km)	Contact pressure z_2 (MPa)	Sliding speed z_3 (m s^{-1})
Zero level: 0	80	7	1
High level: +1	120	13	1.5
Lower level: −1	40	1	0.5
Level space	40	6	1

Table 3
Experimental arrangement and test results[a]

Experiment number	z_1	z_2	z_3	y_1	y_2	y_3
1	40	13	0.5	1.201	0.963	0.875
2	40	7	1	0.581	0.448	0.399
3	40	1	1.5	0.311	0.306	0.299
4	80	13	1	1.298	0.998	0.904
5	80	7	1.5	0.642	0.531	0.465
6	80	1	0.5	0.376	0.357	0.328
7	120	13	1.5	1.334	1.092	1.056
8	120	7	0.5	0.678	0.592	0.553
9	120	1	1	0.487	0.396	0.377
$S=\sum_{i=1}^{9} y_i^2-\frac{1}{9}\left(\sum_{i=1}^{9} y_i\right)^2$				1.2892	0.7384	0.6488

[a] Note: y_1, y_2 and y_3 are the wear volume losses (mm^3) of UHMWPE, PA-6/UHMWPE alloy and PA-6, respectively.

trial of nine experiments was performed once [15]. The test arrangement and results are listed in Table 3. The experimental design matrix showing the level of each factor used for each run, provides the basis for the further analysis.

3.2. Regressive equation between volume loss and its affecting factors

For the convenience of data processing and to calculate the regression coefficient according to code, the investigated parameters were encoded as follows to give normalized variables varying within the range of [−1, 1]:

$$
\begin{aligned}
X_1(z_1) &= 2\frac{z_1-\bar{z}_1}{\Delta_1}=\frac{Z_1-80}{40}\\
X_1(z_2) &= \frac{z_2-\bar{z}_2}{\Delta_2}=\frac{Z_2-7}{6}\\
X_1(z_3) &= \frac{z_3-\bar{z}_3}{\Delta_3}=\frac{Z_3-1}{0.5}\\
X_2(z_1) &= 3\left[\left(\frac{z_1-80}{40}\right)^2-\frac{2}{3}\right]\\
X_2(z_2) &= 3\left[\left(\frac{z_2-7}{6}\right)^2-\frac{2}{3}\right]\\
X_2(z_3) &= 3\left[\left(\frac{z_3-1}{0.5}\right)^2-\frac{2}{3}\right]
\end{aligned}\tag{1}
$$

where $X_1(z_1)$, $X_1(z_2)$ and $X_1(z_3)$ stand for the first order code of sliding distance, contact pressure and sliding speed, respectively; $X_2(z_1)$, $X_2(z_2)$ and $X_2(z_3)$ stand for the second order code of sliding distance, contact pressure and sliding speed, respectively. Here, Δ is the test level space of investigated parameters; N is the test level number of the parameter. Also, $\bar{z}$ is the mean value of the investigated parameter. The coding of the parameters is summarized in Table 4 with the statistical calculation and regression coefficients b. Now, B, D, and b are expressed as follows:

$$
\begin{aligned}
B_{jmk} &= \textstyle\sum_{i=1}^{9}(X_m(z_k)y_j)_i\\
D_{mk} &= \textstyle\sum_{i=1}^{9}(X_m^2(z_k))_i, \quad k=1,2,3;\ m=1,2 \text{ and } j=1,2,3\\
b_{jmk} &= \frac{B_{jmk}}{D_{mk}}
\end{aligned}\tag{2}
$$

Based on the results in Table 4, the regression equations between wear volume (y, cm^{-3}) and each individual parameter as well as their interactions can be obtained.

For the UHMWPE specimens, the regression equation between wear volume loss (y_1, cm^3) and investigated parameters was expressed as

$$
\begin{aligned}
y_1 = 0.7676 &+ 0.0677X_1(z_1) - 0.0022X_2(z_1)\\
&+0.4432X_1(z_2) + 0.0669X_2(z_2)\\
&+0.0053X_1(z_3) - 0.0106X_2(z_3)
\end{aligned}\tag{3}
$$

For the specimens of PA-6/UHMWPE alloy, the regression was expressed as

$$
\begin{aligned}
y_2 = 0.6314 &+ 0.0605X_1(z_1) + 0.0014X_2(z_1)\\
&+0.3323X_1(z_2) + 0.0539X_2(z_2)\\
&+0.0028X_1(z_3) + 0.0087X_2(z_3)
\end{aligned}\tag{4}
$$

For the specimens of PA-6, the regression equation was

$$
\begin{aligned}
y_3 = 0.584 &+ 0.0688X_1(z_1) + 0.0092X_2(z_1)\\
&+0.3052X_1(z_2) + 0.0558X_2(z_2)\\
&+0.0107X_1(z_3) + 0.012X_2(z_3)
\end{aligned}\tag{5}
$$

then, using Eq. (1), the Eqs. (3)–(5) were converted into the following Eqs. (6)–(8), respectively:

$$
\begin{aligned}
y_1 = 0.1159 &+ 2.35\times10^{-3}z_1 - 4.125\times10^{-6}z_1^2 - 4.2\\
&\times10^{-3}z_2 + 5.575\times10^{-3}z_2^2 + 0.265z_3 - 0.1272z_3^2
\end{aligned}\tag{6}
$$

$$
\begin{aligned}
y_2 = 0.7732 &+ 1.0925\times10^{-3}z_1 + 2.625\times10^{-6}z_1^2\\
&+8.9201\times10^{-3}z_2 + 4.492\times10^{-3}z_2^2\\
&-0.2032z_3 + 0.1044z_3^2
\end{aligned}\tag{7}
$$

$$
\begin{aligned}
y_3 = 0.5314 &- 1.04\times10^{-3}z_1 + 1.725\times10^{-5}z_1^2\\
&-0.0142z_2 + 4.65\times10^{-3}z_2^2\\
&-0.2666z_3 + 0.144z_3^2
\end{aligned}\tag{8}
$$

In order to estimate the experimental errors, the fitting results were tested using the results obtained from five repeated tests at conditions of sliding distance of 80 km, contact pressure of 7 MPa and sliding speed of 1.5 m s^{-1}. The repeat results are listed in Table 5. The results of F statistical tests show that Eqs. (3)–(5) correlate well with the results at the degree of confidence of 99% (the confidence level being set at 0.01).

Table 4
Statistical analysis table

Codes	Φ	$X_1(z_1)$	$X_2(z_1)$	$X_1(z_2)$	$X_2(z_2)$	$X_1(z_3)$	$X_2(z_3)$
1	1	−1	1	1	1	−1	1
2	1	−1	1	0	−2	0	−2
3	1	−1	1	−1	1	1	1
4	1	0	−2	1	1	0	−2
5	1	0	−2	0	−2	1	1
6	1	0	−2	−1	1	−1	1
7	1	1	1	1	1	1	1
8	1	1	1	0	−2	−1	1
9	1	1	1	−1	1	0	−2
D	9	6	18	6	18	6	18
B_1	6.908	0.406	−0.04	2.659	1.205	0.032	−0.19
b_1	0.7676	0.0677	−0.00222	0.44316	0.0669	0.0053	−0.01056
B_2	5.683	0.363	0.025	1.994	0.97	0.017	0.157
b_2	0.6314	0.0605	0.00139	0.33233	0.05389	0.00283	0.00872
B_3	5.256	0.413	0.165	1.831	1.005	0.064	0.216
b_3	0.584	0.06883	0.00917	0.30517	0.05583	0.01067	0.012

Table 5
Repeat test results

Repeat number	y_1	y_2	y_3
1	0.639	0.540	0.455
2	0.628	0.519	0.449
3	0.661	0.551	0.429
4	0.680	0.547	0.475
5	0.616	0.555	0.461

3.3. Discussion

Based on the statistics theory, suppose y_{jk} is the sum of the wear volume loss corresponding to the factor j at level k, and $\overline{y}_{jk}$ is the average value of y_{jk}. Then the affecting degree, R_j, of factor j on the wear volume loss is defined as the maximum difference among $\overline{y}_{jk}$, i.e. $R_j = \max(\overline{y}_{jk}) - \min(\overline{y}_{jk})$, $k = 1, 2, 3$. R_j reflects the variation of the volume loss caused by the variation of factor j. The higher the R_j is, the stronger the influence factor j exerted on the result is. So, the importance of factors to the wear can be judged according to the value of R_j. The maximum difference, R_j, of each factor on the wear volume loss was calculated and these are listed in Table 6.

It was revealed that the contact pressure, factor (z_2), for the three investigated materials, had a much higher R_j value than the other two factors. This means that the contact pressure had a much stronger effect on the wear of the materials. It was the leading factor, followed by sliding distance and sliding speed.

Table 6
The maximum difference of factors (R_j)[a]

Factors	Sliding distance	Contact pressure	Sliding speed
UHMWPE	0.14 (0.13)	0.89 (0.83)	0.04 (0.04)
PA-6/UHMWPE	0.29 (0.3)	0.66 (0.67)	0.03 (0.03)
PA-6	0.14 (0.16)	0.70 (0.79)	0.05 (0.06)

[a] Note: relative data in parenthesis.

The influence sequence of the three operating parameters remained the same for all three materials investigated. It followed the sequence of contact pressure, sliding distance, then sliding speed. However, the influence degree of each parameter in the wear of the individual materials was different. Taking the whole contribution of the three parameters to the wear volume as 1, the relative contribution or effect of individual parameters was calculated and these are listed in parentheses in Table 6. It was observed that contact pressure played a relatively more important role in the wear of UHMWPE than in the other two materials, i.e. the wear of UHMWPE is more sensitive to contact pressure than the other two polymers; sliding distance played a relatively more important role in the wear of the PA-6/UHMWPE alloy than in the wear of the other two polymers.

UHMWPE is a relatively soft polymer compared to the other two polymers. Although it possesses self-lubricating properties, it has poor ploughing and cutting resistance [16]. When sliding on the stainless steel counterface, a UHMWPE transfer film occurred. This transfer film can increase the relative roughness of the stainless steel and therefore increase the wear of UHMWPE [3]. Under high pressure, the contact pressure increases, perhaps the friction may lead to raise the surface temperature within the micro-zone of the pin and soften the surface layer of the pin, a micro-deformation occurred within the micro-zone in the surface layer of the test pin. The effect of such wear debris results in the UHMWPE surface being teased up into a wave like striation, and abrasive wear increases. Perhaps this is why the wear of UHMWPE was more sensitive to the contact pressure than the other two materials. PA-6 has a higher surface hardness than UHMWPE, and also has high plough and cutting resistance. Therefore, perhaps third body abrasive wear has less influence than is the case with UHMWPE.

As thermoplastic polymeric materials, the wear of the investigated materials is also affected by the viscoelastic response to changes in strain rate and interfacial temperature. The different viscoelastic response to changes in strain rate, together with the effects of any interfacial temperature changes, results in different effects of contact pressure on individual materials. Clarke and Allen [17] reported that the wear of UHMWPE at low pressure (1 MPa, 1 μm surface roughness) decrease with the increase of sliding speed; while it increases at high pressure (5 MPa, 0.25 μm surface roughness). At the same time, a fluctuating wear rate of PA-6 was observed at both pressure levels (1 and 5 MPa) with the increase of sliding speed. It is generally assumed that increased sliding speed gives rise to elastohydrodynamic or partial elastohydrodynamic lubrication (EHL) through the development of a continuous water film between the polymer and the counterface. Lubrication theory shows that for a given applied load, increases in speed can result in load support from EHL either on an asperity scale or via geometric wedge formation. The partial separation of the interacting surfaces by a wedge of lubricant is likely to weaken the effect of sliding speed on the wear of the specimens investigated. That may lead to the condition that sliding speed exhibits less effect than the other two factors on the wear of the specimens.

When blended with PA-6 with the help of compatilizer HDPE-g-MA, the tiny UHMWPE particles dispersed evenly in the matrix of the PA-6 and formed a new kind of material — PA-6/UHMWPE alloy. In fact, the alloy can be viewed as a "filler reinforced composite", the filler being tiny UHMWPE particles, as observed in Fig. 2. The physical and mechanical properties of the alloy are different from that of its maternal components, UHMWPE and PA-6, as revealed in Table 1. When sliding against a counterface, the tiny UHMWPE particles in the PA-6 matrix may play the role of a lubricating agent and the bond between the UHMWPE and the PA-6 (through HDPE-g-MA) may prevent UHMWPE particles being easily transferred onto the surface of counterface. If so, the relative role of contact pressure may have been reduced and the role of sliding distance increased in the wear of the alloy. Such an argument [16] suggests that changes in the physical and mechanical properties, such as surface hardness, microstructure, etc. resulted in the variations of the relative role of the factors in the wear process of the materials.

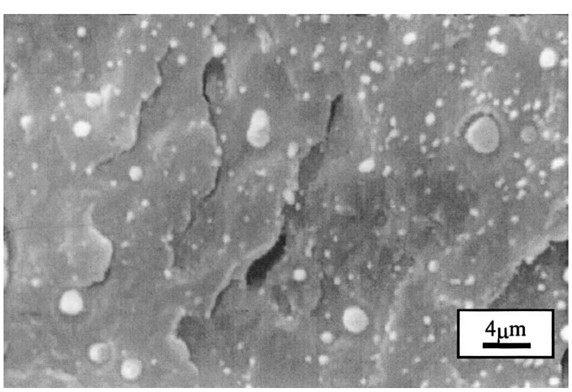

Fig. 2. SEM morphology of PA-6/UHMWPE alloy.

The regression coefficient b_j can also be taken as a measure of the role of the parameter on the wear. The stronger the role of the parameter, the higher the coefficient [15,16]. From the wear regression Eqs. (3)–(5) and Table 4, it was revealed that, during the wear process, the parameter contact pressure (z_2) was the main factor, and sliding distance (z_1) was second. The sliding speed (z_3) had less effect in all cases than other two factors.

The interaction of factors may play an important role in the wear of polymeric materials. Further research needs to be carried out in the future in order to fully understand the interaction of factors on the material's wear performance.

4. Conclusions

The main aim of this research was to analyze the effects of three operating parameters and their interactions on the wear of PA-6/UHMWPE, UHMWPE and PA-6, and to correlate the wear volume with these operating parameters. In particular, the following observations and conclusions were made:

1. A successful attempt has been made to describe the wear behavior of UHMWPE, PA-6/UHMWPE and PA-6 using regression equations. The regression equations between operating parameters and wear volume exhibit a good correlation with experimental measurements within the range of investigation.
2. Contact pressure is the main controlling parameter, followed by sliding distance, while sliding speed plays less effect on the wear of the materials investigated than the other two parameters.
3. The individual operating parameters exerted a different effect on the three materials. The value of the relative degree of effect was dependent on the physical properties of the materials. Among the three investigated materials, UHMWPE was the most sensitive to the contact pressure, while PA-6/UHMWPE was the least; PA-6/UHMWPE was more sensitive to the sliding distance than the other two materials.

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