Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

16th International Conference
on Applied Mechanics and
Mechanical Engineering.

LOAD DEPENDENT WEAR CHARACTERISTICS OF POLYMER-METAL SLIDING

A. Abdelbary*, M. I. El Fahham** and M. E. Elnady*

ABSTRACT

In tribological applications, such as sliding bearing, polymers tends to wear more quickly than indicated in laboratory wear tests. The reason for this discrepancy has been attributed to the effect of loading conditions. In the current study, the influence of loading mode on the wear characteristics of polyamide (PA66) against steel counterpart was investigated in dry and wet sliding conditions. The polymer was tested under different static and cyclic loading conditions in order to provide a comprehensive understanding of its wear behavior. All tests were performed using reciprocating pin-on-plate tribometer which was constructed to perform wear tests under constant and cyclic loads at constant sliding speed. There was consistent evidence of the effect of loading mode on the wear behavior. At cyclic load, the polymer shows significant increase in wear rates than those found under constant load. Furthermore, under wet sliding, the polymer showed generally higher wear rates compared to dry tests.

KEY WORDS

Wear, Polyamide, Cyclic load.

---

* Egyptian Armed Forces, Egypt.
** Faculty of Engineering, Alexandria University, Alexandria, Egypt.

INTRODUCTION

Polymers are being used increasingly in tribological applications due to their high elasticity, good accommodation to shock loading, low friction coefficient and acceptable wear resistance. However, tribological behavior of polymers limits their use in certain applications. External liquid lubricants, which work well for other classes of materials, are easily absorbed by polymers. Furthermore, complexity arises as polymers are easily influenced by the operating and loading conditions. Under fatigue loading, a continuous increase in temperature results in failure of the polymer fatigue sample due to thermal softening. In this situation, fatigue cracks initiate and propagate resulting finally in a fatigue fracture. In fact, the effect of the cyclic parameters on the fatigue behavior of polymeric materials in classical fatigue tests is not far from its effect on the wear behavior under cyclic loading conditions. Working under cyclic loading conditions, as in many mechanical and biomedical applications resulted in a subsurface cracking in the highly strained regions [1].

The effect of cyclic load on the wear behavior of polymers has been detected as a form of surface fatigue wear [2, 3] where a significant increase, 30%, in the wear of ultra-high molecular weight polyethylene UHMWPE was observed when testing the polymer under fluctuating loads. The effect of cyclic load on polymeric wear can be attributed to the loading–unloading cycle which is responsible for creating highly subsurface stressed regions. This in turn, after a number of load cycles, initiates subsurface cracks. Then, the microscopic crack grows by a small amount during the peak load of each cycle. Subsurface crack propagation may accelerate the failure.

Tribological behavior of polymers in lubricated conditions significantly differs from dry contacts due to the effects arising from presence of lubricant. Absorption of water by polymers, plasticization, thermal effects, corrosion of metallic counterface and interference with build-up of transfer films are some conditions which may result in unpredictable tribological behavior of the polymer. Absorption of water molecules from the surface into the bulk polymer can lead to several effects. Available data show that most of the polymers exhibit water absorption level of less than 0.2%, while POM, PMMA, PET, PA 66, and PA6 showed larger values. Among polymers, polyamides have the highest water absorption, which is attributed to the presence of amide groups in its molecular chain, favoring water absorption by forming hydrogen bonds with water molecules owing to their high polarity [4]. These result in a reduction in strength and modulus of elasticity and increase in elongation to break. Swelling of the surface layers leads to differential expansion and possible stress concentrations [5]. The absorption of water and plasticization of polymer surfaces influence the friction and wear of the polymers.

Polyamides (PAs), also known as Nylons, are known as very good tribo-thermoplastics because of a quite good combination of mechanical, tribological and thermal properties along with a moderate cost. Therefore, they are preferred materials in many machine elements such as gears, cams, bearing, etc. However, there are many factors affecting wear of polyamides including loading type (constant or fluctuating), sliding media (dry or lubricant) and other conditions. It is not easy to study a particular factor without considering any unexpected effect could be resulting from another factor. Unlike other polymers, polyamides are known to be particularly affected by ambient water, causing plasticization and having a profound effect on the mechanical properties of the polymer. Reportedly, when water is added to PA66 sliding against itself, there is an immediate reduction in friction and wear resistance as a result of absorbed water reducing the shear strength of the outermost surface layer [6, 7].

The potential of application of polyamides under different operating and sliding conditions demands further study. This would provide a comprehensive understanding of the mechanisms involved in tribology of polymers. Therefore, the present study is aimed at investigating the influence of loading parameters and sliding media on the wear behavior of polyamide 66. The wear tests were performed under constant and cyclic load conditions. The polymer was tested in contact with steel counterface using reciprocating test rig in dry and water-lubricated sliding.

EXPERIMENTAL

Tribometer

The reciprocating test rig used in the present study was constructed and presented in previous work [8] and a brief representation is introduced here for more convenience. Some modifications were made in order to increase the capacity of the machine to perform static load tests parallel to the cyclic load tests. Lubricating technique was also modified to insure a continuous feeding of the lubricant fluid during the test period. The tribometer consists of dual six-stations, Fig. 1 (a, b), where wear tests under constant and fluctuating load can be performed. The amplitudes, means, and frequencies of the cyclic load, as well as the magnitude of static load were easily controllable. The carriage reciprocates with nearly constant linear speed of 0.25 m/s with 310 mm stroke.

Two separated loading systems were mounted on the tribometer desktop, each of them acts on one side of the carriage. The right hand loading system was designed to conduct wear tests under constant load conditions using dead weights. The left hand loading system was realized to perform wear tests under cyclic load circumstances generated by the rotation of an array of 6-sine cams driven by an external motor. When the cam rotates, the cam follower transmits the displacement to a compression spring to generate a sine curve force at the test pin holder.

Bulk polymer, counterface, and environmental temperatures were measured and recorded during test run. K-type Chromel/Alumel thermocouples connected to a Comark electronic thermometer were used for recording all temperature probes.

Materials

All tests in the present work were carried out using Polyamide 66 (Nylon 66) due to its wide use in mechanical engineering applications. The material used was manufactured by *Rochling Plastics*, *USA*, and has a trade name of Sustamide 66. Wear pins were machined from 14 mm solid bar into a rod-shaped projection of 8 mm diameter from the main body of the pin, as shown in Fig. 1(c). At the test beginning, polymer specimen has initially turned (machining) surface of 1.5 µm R_a value. Steel plates, Fig. 1(b), AISI 1050 of dimensions 330×30×3 mm were used as a metallic counterface. The plates were prepared by surface grinding to provide a surface with center line average (R_a) value of 0.2 – 0.4 µm. The grinding direction is parallel to the sliding direction.

Wear Tests

The height of the wear pins were measured periodically after each run and the worn volume V (mm^3) was readily calculated from a simple computer program based on the geometrical form of the pin. Volume loss was plotted against sliding distance X (m) for the applied load F (Newtons). The slope of the straight line section of the curve is defined as the wear rate, WR. In case of tests under cyclic load conditions, the mean load F_{mean} is used in calculations.

Dry and water-lubricated wear tests were conducted to investigate the influence of applied load on the wear rate of PA66 under constant and cyclic loads. Constant load tests were performed under two applied loads (F=90N and 135N). Cyclic load tests were conducted to investigate the wear rate of polymer subjected to cyclic loads of mean value F_{mean}= 90N at two cyclic frequencies (f = 0.25 and 1.50 Hz).

RESULTS

Results of constant load tests, shown in Table 1, indicated that the wear rates of polymer in water lubricated tests was roughly about 5 to 6 times to those tested in dry sliding condition. The wear curves of these tests, shown in Fig. 2, exhibit an interesting observation; they do not show any significant running-in wear regime as found in dry sliding of polymers. Many features observed on the worn surfaces were common to all polymer pins examined in dry conditions. Figure 3 can be considered as a representative of the situation. Grooves run across the surface of the wear pin parallel to the sliding direction; these grooves were present at all stages of the test. On the other hand, polymer worn surface in water-lubricated tests indicated different attitude compared to those performed at dry tests. Polishing, fine scratches and absence of wear grooves were the main characteristics of the polymer worn surface, as shown in Fig. 4.

Table 2, contains wear results of cyclic load tests. It demonstrates a clear increase in wear rate with frequency increase in both dry and water-lubricated conditions. A useful observation is that there was a significant increase in the total worn volume due to cyclic frequency. The importance of such an observation is that in many mechanical and medical polymeric applications, the total volume loss may have a superior priority in calculating the life time of the component. In particular, for short life polyamide bearing, the total volume loss plays a controlling role than the wear rate, since this will affect the dimensional stability of the bearing. In other words, the increase in the total volume loss will increase the clearance between the mating surfaces [9].

DISCUSSION

Constant Load Tests

In dry sliding, as would be expected, the wear rate of polyamide increases with increasing applied load, as shown in Fig. 5. It is broadly known that the mechanism of friction and wear of polymers varies depending on the applied normal load. At high loads, thermal softening of the polymer and plastic deformation at the asperity interactions has a dominant role in determining the real area of contact.

General agreement was confirmed about the effect of water on the wear of polymeric materials. Sliding of thermoplastics in aqueous media results in higher wear rates compared to dry sliding condition [7, 10]. The effect of water on the wear behavior of polymers can be mainly generalized in the following points [11-13]:

i. Water molecules diffuse readily into the free volume of the amorphous phase of the polymer leading to plasticization, swelling and softening, which reduce the hardness and strength of polymer.
ii. Water has the effect of washing action for the counterface surface; therefore, a transfer film similar to that under dry sliding condition failed to form and the polymer slides directly against the metallic counterface. This could be the reason that the wear curves did not show any distinguished running-in phase, Fig. 2(b). It is likely that polymer transfer film, which usually found in dry sliding, of the same tribosystem, failed to form and the slid occurred directly between polymer surface and steel counterpart.
iii. Water might induce an increase in the chemical corrosion wear of the metallic counterface, which would lead to a modification of the surface profile, and finally greater wear rate of polymer is expected. Furthermore, Immersion of steel on water resulting in improving its wettability which, in turn, will hasten polymer wear.

Morphological analysis of the rubbing surface of polyamide 66 confirmed that under dry sliding condition some apparent plastic flow traces, and plowed grooves on the polymer worn surface were detected, as shown in Fig 3. Uniform and continuous transfer film of the polymer was formed on the metallic counterface. This suggests that the wear process was governed by the plastic deformation and mechanical microploughing. On the other side, under water lubricating condition, the worn surfaces were almost smooth and slightly ploughed grooves parallel to the sliding direction were observed, as shown in Fig. 4. This suggested that the wear process was governed by the mechanical microploughing and abrasive wear mechanisms. Temperature measurements of bulk polymer under dry sliding condition (T = 42 ^{o}C) were higher than those under water lubricating condition (T= 25 ^{o}C). Clearly, this is the result of the cooling action of water. Due to the high contact temperature during dry sliding, polymer was softened enhancing the ability of transfer film formation resulting in relatively higher wear resistance than in water lubrication condition where the transfer film is absent.

Cyclic Load Tests

Results of wear tests demonstrated that cyclic load generally results in an increase in the wear rate of polyamide compared to constant load, as shown in Fig. 6. In dry reciprocating sliding when the polymer subjected to a cyclic loading condition, the resulting relatively higher wear rate is contributed to a surface fatigue wear mechanism. The increase in wear rates is attributed to the enhanced wear debris escape rate occurring during the unloaded phase of the load cycle. Wear will occur during the loaded phase due to the asperity interaction, by abrasion, but the debris will be unable to escape due to the high surface conformity as in the constant load tests. While, during the second half of the cycle phase, the surface conformity will decrease and this debris will be free to escape [14]. This is reasonable and acceptable especially in case of wear in lubrication condition where the fluid is playing a part in escaping of the debris into the surrounding. Hence, higher wear rates were found at higher cyclic frequencies, as shown in Fig. 6.

At this group of tests, however, there is another important consideration to be taken into account which is the effect of lubricant film thickness. According to Equation (1), the lubricant film thickness is proportional to the applied load [15]. In the present tests, cyclic applied load have two levels of variation, F_{min} *and* F_{max}, each of which has a corresponding lubricant fluid film thickness (h_o), as shown in Table 3.

$$h_o = \frac{d_{crit}^{\frac{3}{2}}}{4.51}\left(\frac{F}{\eta v}\right)^{\frac{-1}{2}} \tag{1}$$

where,

h_o	Fluid film thickness at the trailing edge of the pin (m).
d_{crit}	Critical wear scar diameter (m).
F	Applied force (N).
η	Viscosity of the lubricant fluid (Ns/m^2).
v	Sliding speed (m/s).

The above observations could be beneficial to explain similar lubricant failure situations. Also, it may underline important aspects to be considered when designing boundary lubricated bearing systems operating under cyclic loading. In such cases, the maximum value of the applied stress as well as the load frequency should be considered in calculations.

Polymer rubbing surface, also, appears relatively smooth and shiny, indicating that the surface had been burnished or lapped. At the end of wear tests, measurements of surface roughness (R_a) of polymer surfaces were found to be in order of 0.2- 0.3 µm while roughness of the steel counterface were about 1.3-1.5 µm. It is suggested that sliding wear of polyamide/steel tribo-systems in water lubricating condition results in roughing the steel counterface and smoothing the polymer surface. The former was obviously due to effect of rust on the metallic surface, while the later seems to be due to surface lapping effect. Optical microscope investigation of the rubbing surfaces showed very fine scratches in the sliding directions, as shown in Fig. 7.

Similar observations were reported in analysis of retrieved components. All of the examined retrieved components demonstrated evidence of abrasion, burnishing and scratching on the articulating surfaces. The wear area appeared very smooth and shiny indicating that the surface had been burnished and also some fine scratching in the direction of sliding was present [16]. Fig. 8 shows similarity of their findings compared with our results.

SUMMARY

The present study has been presented in order to investigate the influence of load parameters on the wear behavior of polyamide 66. The following conclusions summarize the findings from this study.

a) At constant load tests, increasing the applied load resulted in increasing in wear rate in dry and wet sliding conditions. On the other hand, at cyclic load tests the cyclic frequency has a prominent effect on the wear resistance.
b) The change in wear rate at cyclic load tests, from those found at constant load tests, was attributed to the enhanced wear debris escape rate occurring during the unloaded phase of the load cycle as well as the thickness of the lubricant film.
c) The high wear rates of polyamides are attributed to the plasticization caused by water absorption.

REFERENCES

[1] Cooper, J. R., Dowson, D., & Fisher, J. (1994). Observations of a residual subsurface shear strains in ultrahigh molecular weight polyethylene acetabular cups. Journal of Material Science: Material in Medicine, 5: 52-57.

[2] Hu, X., Harringlon, E., Marquis, P. M., & Shortall, A. C. (1999). The influence of cyclic loading on the wear of a dental composite. Biomaterials, 20(10): 907-912.

[3] Yap, A. U. J., Teoh, S. H., & Chew, C. L. (2002). Effect of cyclic loading on occlusal contact area wear of composite restoratives. Dental Materials, 18(2): 149-158.

[4] Prakash, B., & Hogmark, S. (2010). Selected papers from those presented at the 14th Nordic Symposium on Tribology (Nordtrib 2010) Storforsen, June 8–11, 2010. Wear, 273 (1): 1.

[5] Yuji Yamamoto and Tadashi Takashima, Friction and wear of water lubricated PEEK and PPS sliding contacts, Wear, 253 (2002) 820–826.

[6] Barbara Stuart and Brian Briscoe, Surface plasticisation of Nylon 6,6 by water, Polymer International, 38 (1995) 95-99.

[7] A. Abdelbary, M. N. Abouelwafa, I. El Fahham and A.H.Hamdy, The effect of surface defects on the wear of nylon66 under dry and water lubricated sliding, Tribology International, 59 (2013) 163–169.

[8] A. Abdelbary, M.N. Abouelwafa, I.M. El Fahham and A.I. Gommaa, A new reciprocating tribometer for wear testing under different fluctuating loading conditions, Alexandria Engineering Journal, 43 (2004) 615-619.

[9] Freber K., Atkenson J.R. and Dowson D., "The Mechanisms for Nylon 66" Paper II, *Proceeding of the 3rd Leeds-Lyon Symposium on Tribology*, September 1976.

[10] Tanaka, K. (1980). Friction and wear of semicrystalline polymers sliding against steel under water lubrication. Transaction of the ASME, Journal

of Lubrication Technology, 102(4): 526-533.

[11] Yamamoto, Y., & Takashima, T. (2002). Friction and wear of water lubricated PEEK and PPS sliding contacts. Wear, 253(1-2): 820-826.

[12] Yu, S., Hu, H., & Yin, J. (2008). Effect of rubber on tribological behaviors of Polyamide 66 under dry and water lubricated sliding. Wear, 265(3-4): 361-366.

[13] Meng, H., Sui, G. X., Xie, G. Y., & Yang, R. (2009). Friction and wear behavior of carbon nanotubes reinforced Polyamide 6 composites under dry sliding and water lubricated condition. Composites Science and Technology, 69(5): 606-611.

[14] Barbour P.S.M., Barton D.C., Fisher J., "The Influence of Contact Stress on the Wear of UHMWPE for Total Replacement Hip Prostheses", Wear, Vol. 181-183, 1995, pp. 250-257.

[15] Lancaster, J. K., Lubrication of carbon fiber-reinforced polymers; Part I: Water and Aqueous Solutions, Wear, 1972, 20(3): 315-333.

[16] Letita Bradford, David A., and Pruitt L.A., "Wear and Surface Cracking in Early Retrieved Highly Cross-Linked Polyethylene Acetabular Liners", Journal of Bone and Joint Surgery, 2004, pp. 1271-1282.

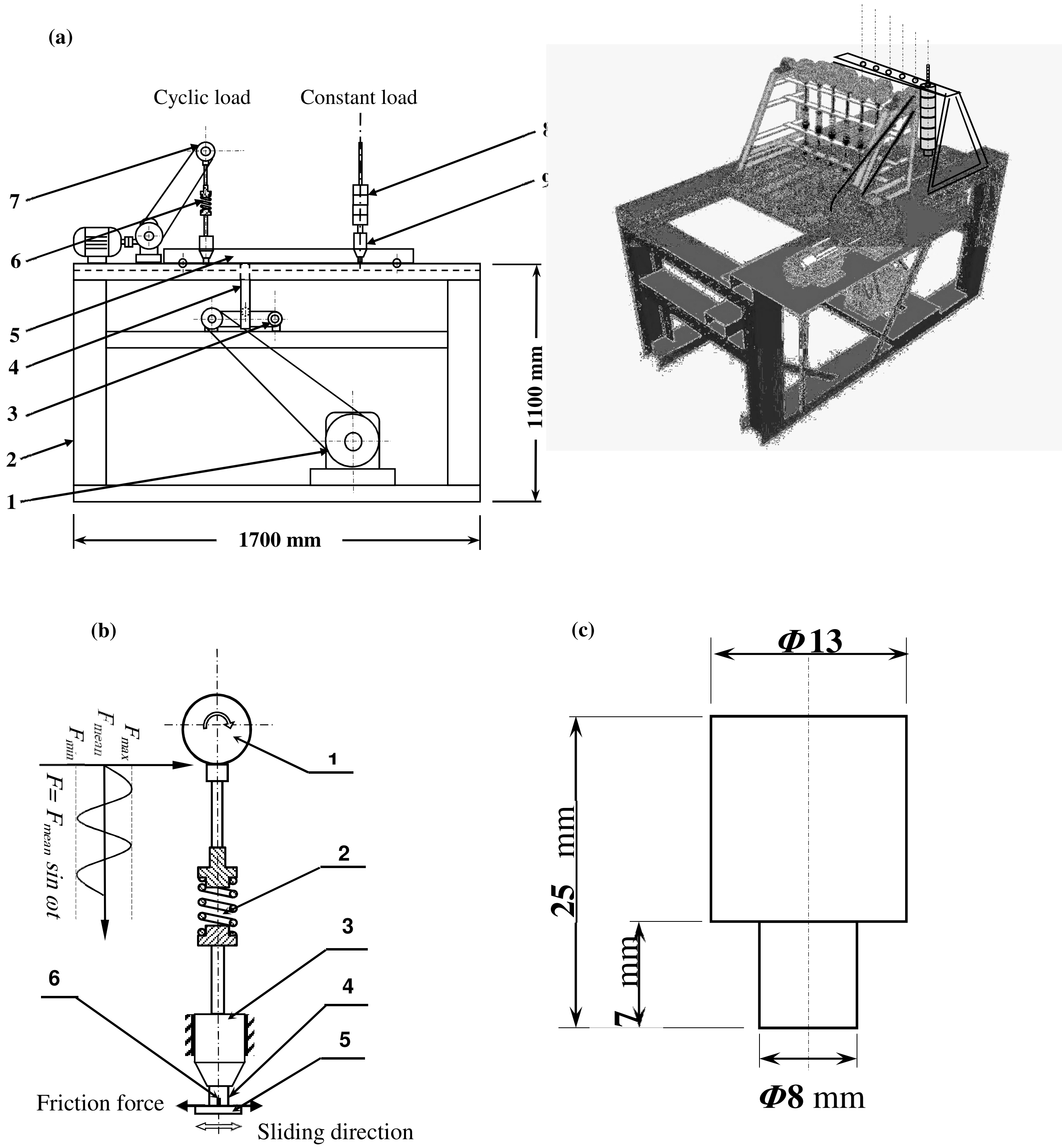

Fig. 1. (a) Tribometer; (1) motor; (2) machine frame; (3) chain drive mechanism; (4) U-beam guide; (5) reciprocating carriage; (6) spring; (7) eccentric cam; (8) dead weights; (9) pin holder.

(b) Cyclic load system: (1) eccentric cam; (2) compression spring (3) pin holder; (4) polymer specimen; (5) steel counterface; (6) imposed crack.

(c) Wear pin geometry.

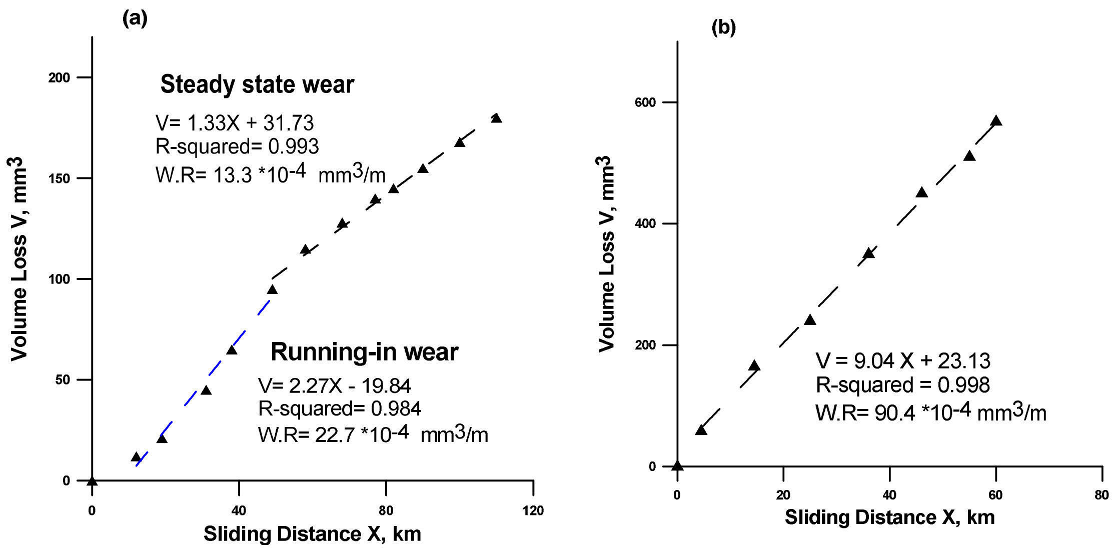

Fig. 2. Variation of PA66 volume loss with sliding distance at 90 N applied load (a) dry and (b) wet.

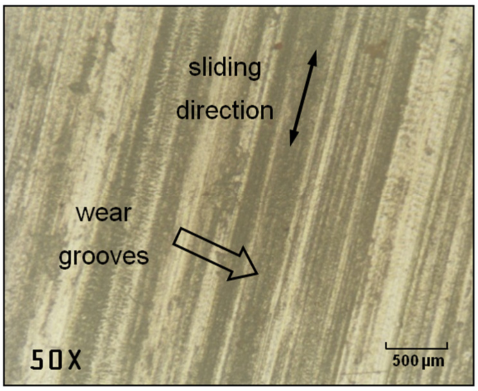

Fig. 3. PA 66 worn surface after 80 km of sliding, *F*=90 N.

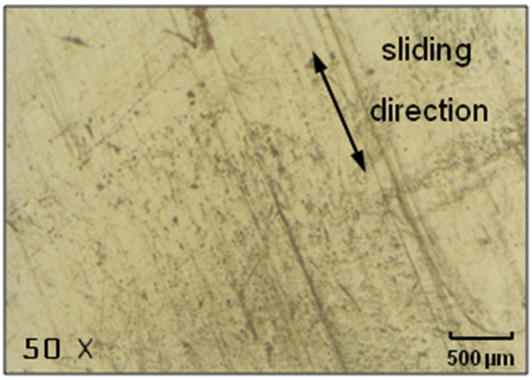

Fig. 4. PA 66 worn surface after 40 km sliding distance, at 90 N applied load.

Fig. 5. Variation of PA66 wear rate WR with constant load in dry and water-lubricated sliding conditions.

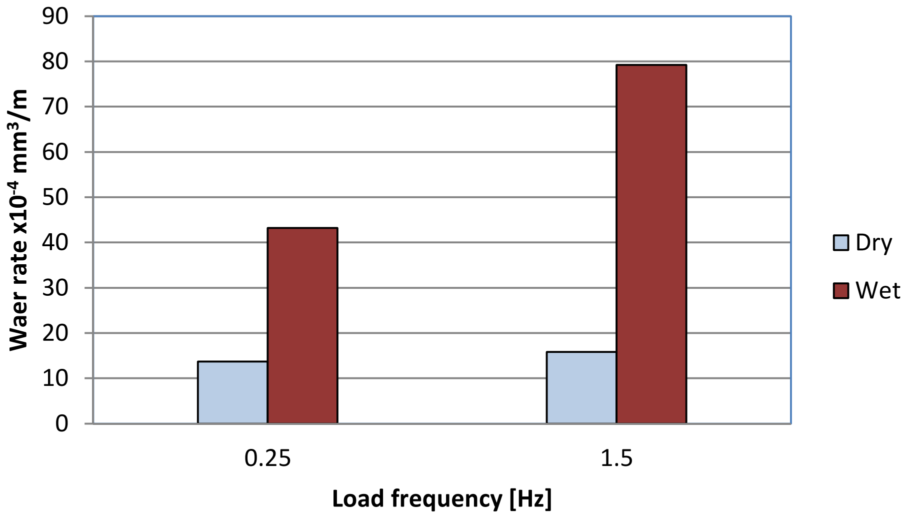

Fig. 6. Variation of PA66 wear rate WR with cyclic load in dry and water-lubricated sliding conditions.

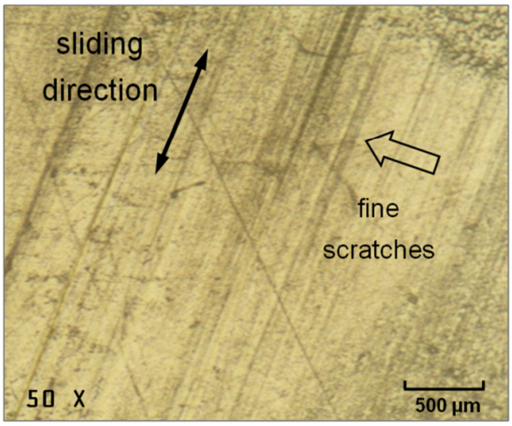

Fig. 7. PA 66 worn surface after 40 km sliding distance (F_{mean}= 90N, f= 1.5 Hz).

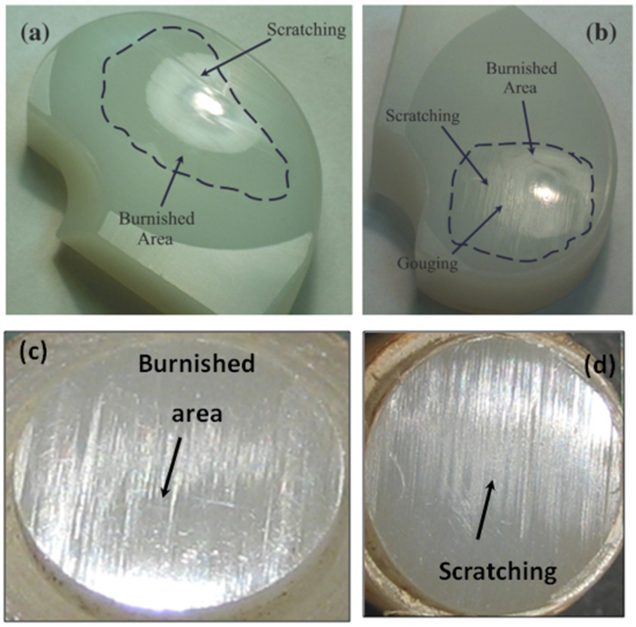

Fig. 8. (a, b) worn/burnished areas and some slight scratching and gouging of UHMWPE tested in orthopedic wear simulator, adopted from Ref. [14], (c, d) scratching and burnished area of wear surfaces of PA66 (F_{mean}= 90N, f= 1.5 Hz).

Table 1. Results of constant load tests in dry and wet sliding conditions.

Sliding condition	F N	p MPa	Steady state wear		
			X km	V mm^3	WR x10^{-4} mm^3/m
Dry	90	1.8	110	180	13.3
Wet			60	568	90.4
Dry	135	2.7	90	217	18.1
Wet			60	583	95.7

Table 2. Results of cyclic load tests in dry and wet sliding conditions.

Sliding condition	f Hz	Steady state wear		
		X km	V mm^3	WR x10^{-4} mm^3/m
Dry	0.25	80	130	13.7
Wet	0.25	51	215	43.2
Dry	1.50	100	191	15.8
Wet	1.50	57	428	79.2

F_{mean} = 90 N, F_{max} = 170 N, p = 1.8 MPa

Table 3. Water fluid film thickness (***h_o***) values w.r.t. applied load.

Cyclic Load N	h_o µm
F_{min} = 10	0.73
F_{max} = 170	0.17

Data used in calculation (d_{crit} = 0.008 m, η=8.9*10^{-4} Ns/m, v= 0.24 m/s)