THE COMPARATIVE STUDY OF POLYMERS FOR SLIDING PAIRS WITH UNMT (UNIVERSAL NANO/MICRO TESTER)

A. Król[1*], K. Gocman[2]

[1]Military University of Technology, Faculty of Mechanical Engineering, 2 Gen. Kaliskiego Str., 00-908 Warsaw, Poland, tel.:+48 261839410, email: artur.krol@wat.edu.pl

[2]Military University of Technology, Faculty of Mechanical Engineering, 2 Gen. Kaliskiego Str., 00-908 Warsaw, Poland, tel. +48 261839693, email: krzysztof.gocman@wat.edu.pl

ABSTRACT

In the article the results of comparative research of eight types of polymers, used in sliding pairs, are presented. For the selected polymers mechanical properties and then also their tribological characteristics were examined with UNMT (UNMT - Universal Nano/Micro Tester) to select the best material. Friction coefficient and wear measurements were performed with reciprocating ball-on-disk pair of UNMT under dry lubrication conditions. The usefulness of UNMT was confirmed as a quick and precise method. Presented results showed also that the best antifriction and anti-wear properties were observed for polymer with small hardness and elasticity module.

Keywords: tribological characteristics, polymers, wear, UNMT

*Corresponding author: Artur Król (artur.krol@wat.edu.pl)

INTRODUCTION

Polymers are excellent material in mechanical engineering, as they are easy in manufacturing at low costs and mainly present great tribological performance [1]. Among most popular polymers used in sliding pairs are polyamides (PA), polyoxymethylenes (POM) and polytetrafluoroethylene (PTFE), as they are very attractive industrial polymers for engineering and tribology applications [1]. They are manufactured and applied in pure state and are the matrix of various composites, being still developed to decrease their disadvantages.

PAs are popular as they present a high mechanical strength and stiffness, a high creep resistance as well as excellent thermal and tribological properties under normal operating conditions [1–4]. They are used as a replacement for bronze, brass, aluminium or steel parts, including rollers and guides, bushings and bearings, etc. due to their good dry sliding properties [2]. However, they have also some disadvantages, such as strong water-absorptivity, instability of structural sizes, high shrinkage and also a higher coefficient of friction and wear rate and the worse friction stability under high load condition [4]. Thus there are numerous authors [2–7] presenting their studies on the performance of PA reinforced and modified by fillers.

POM also show good wear and abrasive resistance and also good toughness and strength [4]. In addition, they also have a low coefficient of friction and low water absorption. Their disadvantages are their high mould shrinkage and higher specific gravity [1, 4, 8]. There are also numerous works presenting composites based on POM matrix, as in [6] where authors tested the influence of carbon nanotubes (CNTs) on the specific wear rate of POM/CNT nanocomposites by using a pin-on-disk test rig. The specific wear rate (Ws) for POM/CNT containing 0.03 wt.% CNT in air and water media was improved and also the tensile strength of the mechanical properties and Young's modulus were increased.

PTFE is the polymer widely implemented in engineering, as lubricant additive, antifriction coatings, low-friction seals etc., based on its unique combination of low friction, low chemical reactivity and large temperature range [1, 9]. However the high wear rate, poor mechanical properties and low resistance to creep are the main reason of limited use of PTFE as a solid lubricant [1, 9, 15]. Thus as for PA and POM, the main tendency of PTFE improvement is its reinforcement and modification by glass fibers or carbon fibers [9, 10] and by nanocompositities, what is especially promising [1]. The authors in [1] showed the wear reductions of nearly two orders of magnitude for nanocompositities comparing to microcomposites.

Summarizing, the actual trends of polymers and composites development towards tribology applications are research of various fibers, especially carbon fibers, and improving their adhesion to matrix [7, 9], surface modification, design of new nanocomposites, with nanoparticles, nanofibers [1] or nanotubes [12], polymer use in micromachines such as MEMS [1] and also design of new composite coatings on metals or other materials [11–13].

Research of polymers properties for tribological pairs should be performed with accurate and strict methods, enabling quick selection of the best material. Generally tribological performance of polymers and composites is examined on the small-scale tester, due to small cost or time-efficiency and flexible handling of test specimens [2]. However, the problem of scale in tribotesting should be regarded [2, 3], as the most reliable and applicable results can be achieved in a real tribosystem. Preparing the program of the research the various conditions should be regarded, as material structure, contact conditions, sliding motion and velocity and energy disspation [2, 3]. The UNMT tester with wide range of available modulus in different scale seems to be an attractive tool to quick selection and comparing research for general purpose and for composites in macro and microscale.

The use of UNMT in research of tribological characteristics of different materials is well known and fully presented [9, 11–13]. The tester is generally used in the research of various coatings, as in [11], where the friction characteristics of a fluoropolymer coating were investigated in relation to fretting process as a function of load, velocity and displacement amplitude. In the next article [12] the attention was put on microelectromechanical systems (MEMS). Ultra-thin layer of PFPE was dip-coated onto two different self-assembled monolayers (SAMs) and checked for their tribological characteristics with use of Universal Micro Tribometer (UMT) in ball-on-disc mode. That gave the authors to achieve more realistic sliding contact area and higher sliding speed than in atomic force microscope (AFM) with the lateral force measurement option. Also in [13] the authors presented the results of unlubricated sliding friction and wear tests of carbide-derived carbon (CDC) coatings on SiC and Ti3SiC2 blocks, conducted on a UMT-2MT tribometer with a ball-on-block configuration.

UNMT tester is also used in testing of various composites and polymers, but not so frequently as for coatings [2, 9, 14]. In [9] the authors examined tribological properties of the PTFE composites, sliding against GCrl5 steel under water-lubricated condition on a reciprocating ball-on-disk UMT. Mechanical properties and tribological characteristics of ultra-high molecular weight polyethylene (UHMWPE) samples were tested on the UNMT in [14].

The key goal of the article is to check mechanical, friction and antiwear properties of chosen commercially available polymers and composites in order to select the material with the best performance. The tests were performed on the UNMT tester with ball-on-disk modulus for friction and antiwear properties.

EXPERIMENTAL PROCEDURE

Materials

Commercially available materials of two producers, recommended for the sliding pairs, were chosen for the tests. They cover three main groups: polyamides (PA), polyoxymethylenes (POM) and polytetrafluoroethylenes (PTFE). They were pure polymers and their composites, as follows: PTFE –2 pure types, polyamides PA-6 (pure, with MoS_2 additive, with lubricant, with 30% of fibreglass), POM - 2 pure types.

Mechanical properties

Mechanical properties of tested polymers were measured in the indentation tests with continuous measurement of depth (h) and normal load (P) – the normal force control was used in the indentation experiment and the indenter depth was dependent on the load. 3.2 mm AISI 52100 bearing ball was used as an indenter, up to maximum load of 4.0 N and with use of precise capacitance sensor of indentation depth. Hardness H and elastic modulus E were determined by means of the Oliver and Pharr analysis method, using the following formulas [15]:

$$H = \frac{P_{max}}{A} \tag{1}$$

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}} \tag{2}$$

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\upsilon_i^2)}{E_i} \tag{3}$$

where P_{max} is the peak indentation load, A is the projected contact area, S $(=dP/dh)$ is the contact stiffness, v is the Poisson's ratio of the tested material, and E_r is the reduced modulus of elasticity integrating the effect of elastic deformation from the indenter. E_i and v_i are respectively, the modulus of elasticity and Poisson's ratio of indenter (bearing steel). The test were performed on UNMT tester, presented in Figure 1.

Friction and wear tests

The friction and wear tests were performed on a reciprocating ball-on-disk UNMT tribometer, universal microtribometer, controlled by the computer (Figure 1 and Figure 2).

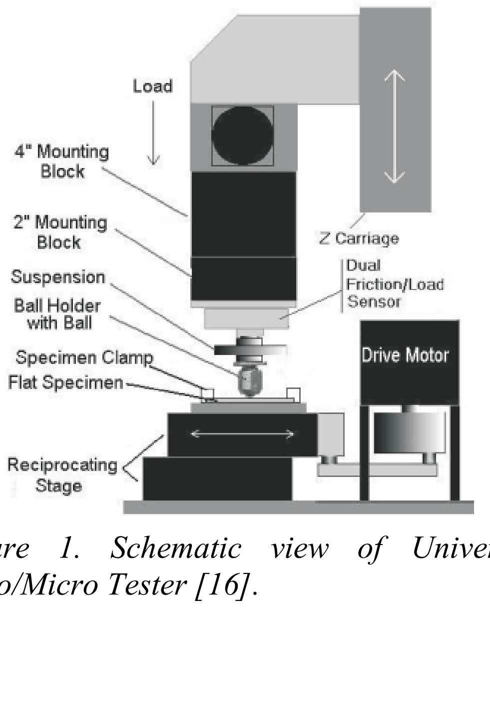

Figure 1. Schematic view of Universal Nano/Micro Tester [16].

Figure 2. General view of Universal Nano/Micro Tester and tribological pair.

The tests were executed under the constant normal load of 2.79 N, at a room temperature with a relative humidity of 45–55% under dry sliding conditions. AISI 52100 bearing steel ball with diameter of 3.2 mm, was used as a counterpart and the polymer disks were prepared for friction tests.

Other parameters were as follows: stroke 1 mm, frequency 20 Hz and duration 3600 s. During the test friction force, the wear depth (using position coder of upper drive) were continuously measured. Finally, after wear tests width of wear scars was measured using optical microscope (Nikon LV100D).

RESULTS AND DISCUSSION

Indentation hardness and elastic modulus

The typical load-depth curves of eight materials are plotted in Figure 3. The large variations of the indentation depths show their distinctions in the material's ability against deformation or the hardness. The highest initial unloading slope for both POM and PA with fibreglass suggests the highest contact stiffness and elastic modulus.

Main parameters obtained on the basis of indentation curves, including hardness and elastic modulus, are shown in Table 1.

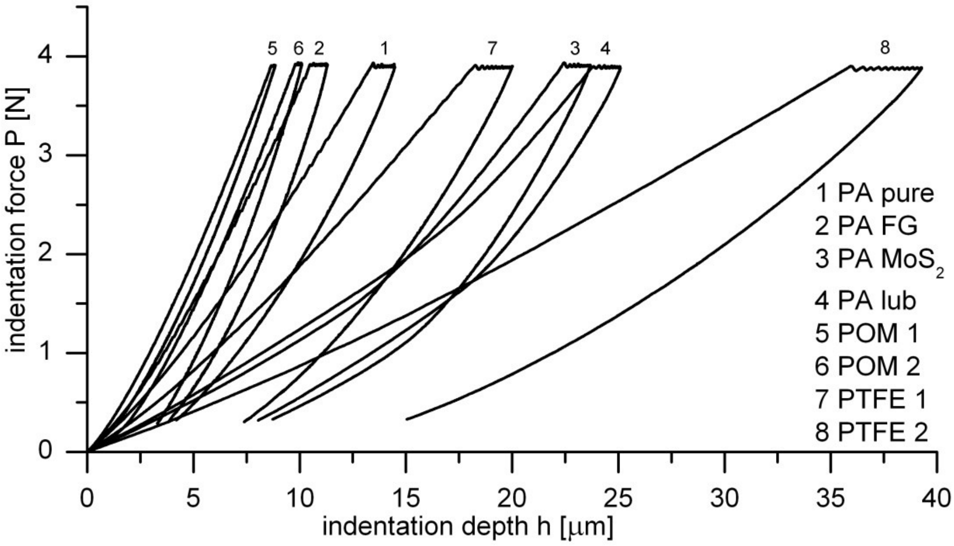

Figure 3. Typical indentation force versus indentation depth curves for tested polymers.

Table 1. The main mechanical parameters obtained on the basis of indentation curves.

Sample	max. depth h_{max} [µm]	contact depth h_c [µm]	contact stiffness S [N/µm]	hardness H [MPa]	elastic modulus E [GPa]
PA pure	14,62 ± 0,16	8,74 ± 0,21	0,50 ± 0,01	44,7 ± 1,2	1,26 ± 0,01
PA FG	11,13 ± 0,44	6,91 ± 0,47	0,69 ± 0,02	56,5 ± 4,1	1,99 ± 0,07
PA MoS_2	23,80 ± 0,19	16,54 ± 0,24	0,40 ± 0,00	23,7 ± 0,6	0,74 ± 0,01
PA lub	25,18 ± 0,17	17,38 ± 0,18	0,37 ± 0,00	22,3 ± 0,6	0,67 ± 0,01
POM 1	8,87 ± 0,08	4,47 ± 0,09	0,67 ± 0,01	87,0 ± 2,0	2,50 ± 0,02
POM 2	9,90 ± 0,36	5,85 ± 0,39	0,73 ± 0,01	67,3 ± 4,2	2,38 ± 0,07
PTFE 1	20,30 ± 0,67	13,25 ± 0,70	0,41 ± 0,00	29,3 ± 1,2	0,80 ± 0,02
PTFE 2	38,36 ± 1,48	24,81 ± 0,70	0,22 ± 0,01	15,3 ± 0,6	0,30 ± 0,02

The values listed in the table correspond to presented indentation curves (unloading slope, indentation depth). The highest values of hardness (more than 55 MPa) as well as elastic modulus (2 GPa and more) were calculated (Oliver and Pharr method [15]) for both polyoxymethylenes and polyamide with fibreglass. In contrast, PTFE shows almost six times lower hardness and more than eight times lower elastic modulus. Furthermore, one can observe that the addition of fibreglass to polyamide resulted in an 25% increase in hardness and more than 50% increase in elastic modulus. However, the additive of molybdenum disulfide and lubricant to PA structure resulted in almost 50% decrease in hardness and more than 40% decrease in modulus. It was also found, that for all polymers there is a strong correlation between hardness and elastic modulus (Figure 4).

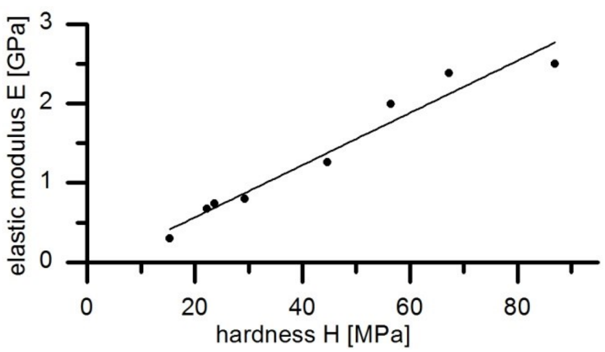

Figure 4. Elastic modulus vs. hardness for all tested polymers.

Tribological properties

The evolution of friction coefficient for the reciprocating tests with frequency of 20 Hz at applied load of 2.79 N and duration of 3600 s for all tested polymers is shown in Figure 5. Generally, the friction coefficient gradually increased with increasing sliding distance (except for the PA with fibreglass), reaching a steady state value μ_{st} after various period of time, depending on the type of the polymer.

One can observe the increase of the friction coefficient from about 0.2 (0.1 for PTFEs and PA with MoS_2) to stabilized values from the very wide range – 0.09–0.8 (Figure 6). The best lubricating abilities (the lowest value of stabilized friction coefficient) were registered for polyamide with additive of MoS_2 (solid lubricant) – μ_{st} below 0.1. Quite low value of friction coefficient were registered for PA with fibreglass and for both PTFEs (0.2–0.3). The highest stabilized value of friction coefficient one can observe for pure PA (~0.8) and for PA with lubricant (~0.7). In both cases the stabilization of μ lasted longer in comparison to other friction pairs.

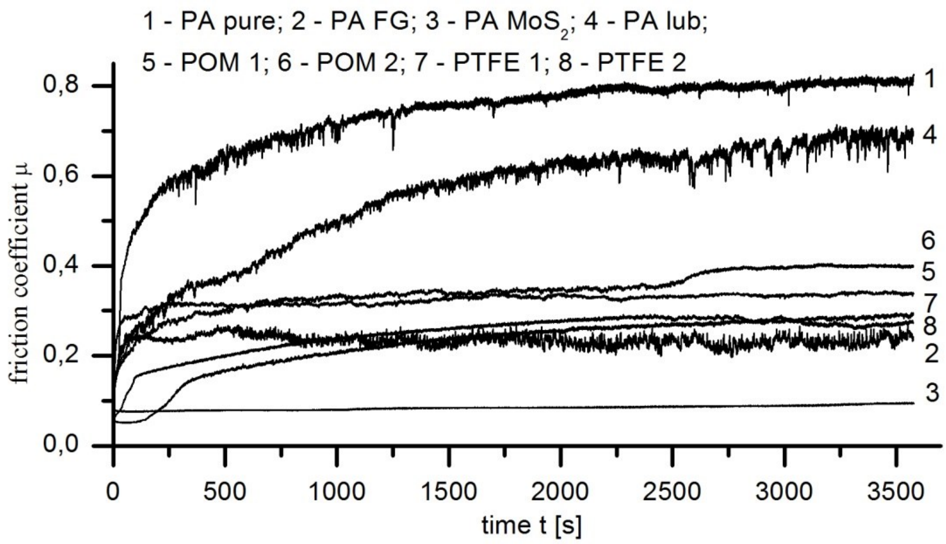

Figure 5. Typical indentation force versus indentation depth curves for tested polymers.

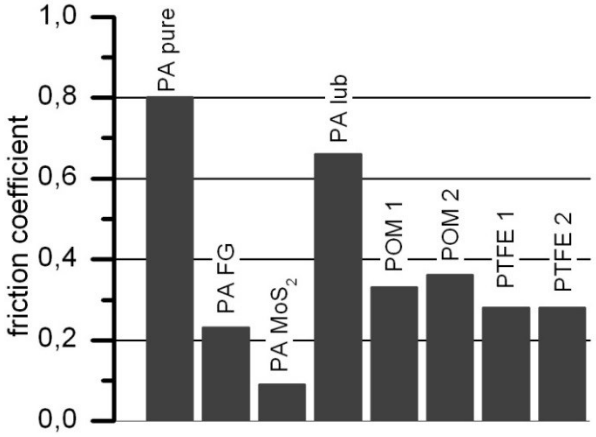

Figure 6. Stabilized value of friction coefficient.

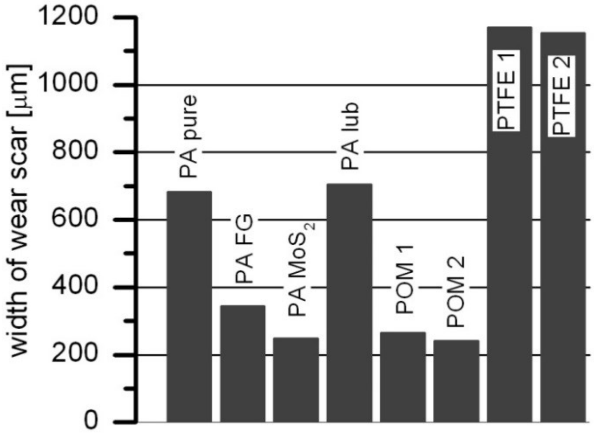

Figure 7. Width of wear scar after the test.

The best tribological properties was characterized by polyamide with molybdenum disulfide additive. The presence of solid lubricant (MoS_2) in friction coupling caused that, despite rather low hardness, the PA with MoS_2 not only has the lowest value of friction coefficient but also shows very good wear resistance (comparable to the hardest POMs). The analysis of wear proved that wear resistance is not always dependent on friction coefficient (Figure 7). In spite of the fact that PTFEs were characterized by quite low values of friction coefficient (below 0.3), they turned out to have the lowest resistance to wear (wear scar width visibly over 1 mm, wear depth ~70 μm). Poor wear resistance of PTFEs probably result from their low hardness (which is usually strongly correlated with wear resistance). That relationship between hardness and wear resistance confirms the dependence plotted in Figure 8 (data for PA MoS_2, due to the strong influence of solid lubricant on final result, was skipped) – wear resistance is directly proportional to the hardness of material (Archard's, Rabinovich's, Khrushchov's formulas).

Microscopic observations revealed the morphology of worn surfaces after friction tests against steel ball. Microphotographs (Figure 9) show, that abrasive wear was dominant mechanism of wear, due to the presence of scratches parallel to the sliding direction. It is also clearly seen that the highest value was observed for PTFE1 and the smallest for PA with MoS_2, presenting also the best antiwear performance within the group of PA. However for pure polymers, there were also almost no difference in width scar, i.e. both POM and PTFE showed the same wear properties.

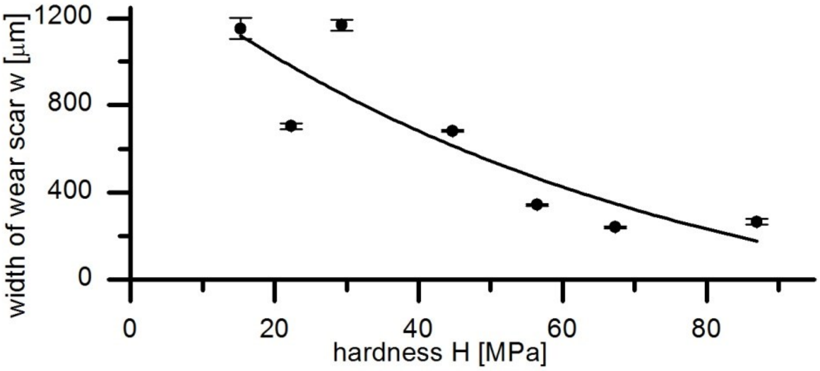

Figure 8.Width of wear scar vs. hardness for tested polymers (except PA with MoS_2).

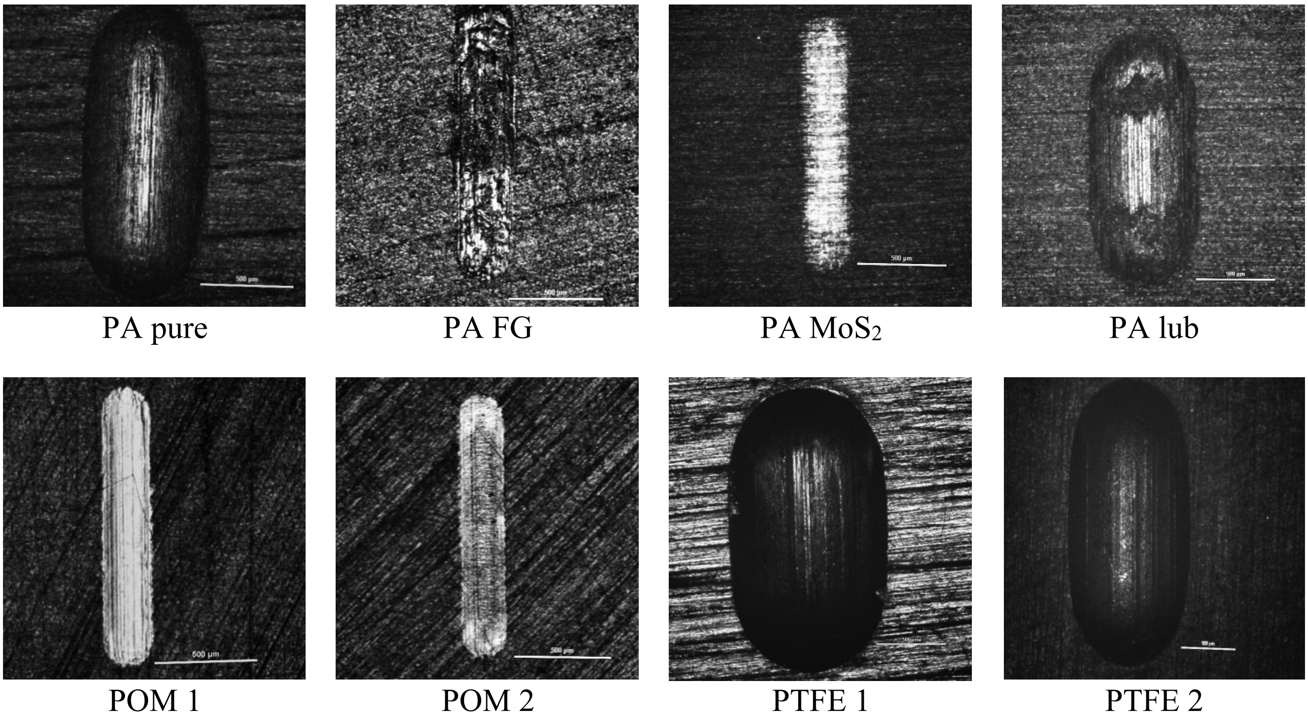

Figure 9. Microscopic photographs of wear scars, mag. 2.5x10, scale bar 500 µm, bright field.

CONCLUSIONS

Comparison on the mechanical and tribological properties of the selected polymer materials coatings was made. The following conclusions can be drawn:

- Tests of mechanical properties showed wide variation of hardness and elastic modulus and a strong correlation between the parameters was found.
- The best antifriction and antiwear performance was observed for PA with MoS2 having relatively low hardness, comparable with PTFE samples. The modification of PA polymer turned out to be the most effective.
- The worst mechanical and antiwear performance was observed for both PTFE samples, instead of quite low friction coefficient.
- UNMT tester for testing of mechanical and tribological characteristics could be excellent tool for quick and precise selection of polymers and composites, regarding implementation in sliding pairs.

REFERENCES

1. Friedrich, A. K. Schlarb, Tribology of Polymeric Nanocomposites - Friction and wear of bulk materials and coatings, 2nd ed., Butterworth-Heinemann, UK, 2013.
2. P. Samyn, T. M. Tuzolana, Effect of test scale on the friction properties of pure and internal-lubricated cast polyamides at running-in. Polymer Testing 26 (2007) 660–675.
3. P. Samyn, P. De Baets, G. Schoukens, I. Van Driessche, Friction, wear and transfer of pure and internally lubricated cast polyamides at various testing scales. Wear 262 (2007) 1433–1449.
4. Li Du-Xin, Li Wen-Juan, Xie Ying, Li Xiang-Xiang, Effects of Solid Lubricants on Friction and Wear Behaviors of Polyamide 6. Journal of Applied Polymer Science 124 (2012) 4239–4248.
5. A. Pogaćnik, M. Kalin, Parameters influencing the running-in and long-term tribological behaviour of polyamide (PA) against polyacetal (POM) and steel. Wear 290–291 (2012) 140–148.
6. S. Yousef, A.M. Visco, G. Galtieri, J. Njuguna, Wear Characterizations of Polyoxymethylene (POM) Reinforced with Carbon Nanotubes (POM/CNTs) Using the Paraffin Oil Dispersion Technique. The Journal of The Minerals, Metals & Materials Society 68 (1) (2016) 288–299.
7. J. Li, X.H. Cheng, Friction and wear properties of surface-treated carbon fiber-reinforced thermoplastic polyimide composites under oil-lubricated condition. Materials Chemistry and Physics 108 (2008) 67–72.
8. C.A. Harper, Handbook of Plastics Technologies: The Complete Guide to Properties and Performance, McGraw-Hill, New York, 2006.
9. Bao Dandan, Cheng Xianhua, Evaluation of Tribological Performance of PTFE Composite Filled with Rare Earths Treated Carbon Fibers under Water-Lubricated Condition. Journal of Rare Earths 24 (2006) 564–568.
10. Shibo Wang, Li Pan, Qian Li, Tribological Behaviors of Polytetrafluoroethylene Composites Under Dry Sliding and Seawater Lubrication. Journal of Applied Polymer Science 130 (2013) 2523–2531.
11. Dae Kyun Baek, M.M. Khonsari, Friction and wear of a rubber coating in fretting. Wear 258 (2005) 898–905.
12. N. Satyanarayana, Sujeet K. Sinha, Tribology of PFPE overcoated self-assembled monolayers deposited on Si

surface. Journal of Physics D: Applied Physics 38 (2005) 3512–3522.

13. J. Sui, J. Lu, Formulated self-lubricating carbon coatings on carbide ceramics. Wear 271 (2011) 1974-1979.
14. Shibo Wang, Shirong Ge, The mechanical property and tribological behaviour of UHMWPE: Effect of molding pressure. Wear 263 (2007) 949–956.
15. W.C. Oliver, G.M. Pharr, An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. Journal of Materials Research 7 (6) (1992) 1564–1583.
16. Bruker Application Note: Ball on Flat Sliding Wear Test Using the Micro-Tribometer mod. CETR-UMT 2 ASTM G133-95 (reapproved 2002), http://www.cetr.com/eng/services/astm-tests.html.