CHARACTERIZATION OF SOME TYPES OF POLYMERS BY FRICTION BEHAVIOUR

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Abstract – The authors developed an experimental methodology to determine the friction forces and friction coefficient in dry and lubricated conditions between steel cylinder and some types of polyurethanes. The method consists in sliding of a steel cylinder on a polymer flat sample in the direction of the cylinder axis. The experiments were realized using the TRIBOMETER UMT-2 (CETR) at normal loads between 1 N and 15 N and with cyclic linear speeds of 1mm/s, 5mm/s and 10 mm/s. A lot of 8 different types of polyurethane were experimentally tested and the friction forces and friction coefficients have been determined according to normal load, sliding velocity and dry and lubricated conditions.

Keywords – Polyurethanes friction tests, friction coefficient, friction forces, dry and lubricated conditions

1. Introduction

Polymers and its composites are extensively used in macro sliding/rolling tribosystems such as gears, sliding and rolling bearings, sealing systems. Also, the thin polymer layers are used in the micro sliding tribosystems such as micropumps, microturbines, microgrippers, micromotors. The most important contributions of the polymers in a tribosystems consist in low friction coefficient and damping of the shocks and vibrations. Different polymers like polyamides (PA), polyimides, polyethylene (PE), polystryrene (PS), polytetrafluorethylene (PTFE) and polymethylmethacrylate (PMMA) are known to have good friction behavior [1]. The friction force depend on roughness of the rubbing surfaces, relative motion, type of material, temperature, normal force, relative humidity, vibration etc. The parameters that dictate the tribological performance of polymer and its composites include polymer molecular structure, processing and treatment properties, viscoelastic behavior, surface texture, etc [2].

To determine the friction coefficient of the polymers in a sliding steel-polymer tribosystem is a complex problem due to minimum two factors: the experimental methods to evaluate friction coefficient and the chain mobility of the polymer structure as a result of the contact stress, speed, temperature [3]. Thus, Verheyde et al. [4] adapted the laser cladding technology to coat thermoplastic polyurethane substrates with thick polyamide 11 (PA 11) composites containing molybdenum disulfide (MoS₂) or PTFE as filler material. A reduction of 80% of the frictional force was measured during ball-on-disc tribotesting. Li et al. [5] investigated the effects of surface texture on the friction of a poly(dimethylsiloxane) (PDMS) disk sliding against a bearing steel ball under water lubrication.

Friction tests were carried-out on the universal Tribometer UMT-CETR in pin-on-disk configuration. The friction coefficient between the bearing steel ball (diameter of 8 mm, hardness of 62-66 HRC and surface roughness Rₐ=0.025 μm) and a PDMS disk were measured at normal loads of 0.95 N and 1.88 N within the sliding speed range from 20 to 200 mm/s. Li et al. [5] found that surface texture is capable of reducing friction at low sliding speed, as well as increasing friction at high sliding speed condition.

Using a pin-on-disk configuration, Chowdhury et al. [2] experimentally investigated the friction coefficient of PTFE and nylon disc sliding against smooth (Rₐ=0.3 μm) or rough (Rₐ=3 μm) mild steel pin having 6 mm diameter at normal load of 10 N, 15 N and 20 N, sliding being 1m/s, 1.5m/s and 2 m/s. Results show that friction coefficient is influenced by duration of rubbing, normal load and sliding velocity. In general, friction coefficient increases for a certain duration of rubbing and after that it remains constant for the rest of the experimental time. The obtained results reveal that friction coefficient decreases with the increase in normal load. On the other hand, they also found that friction coefficient increases with the increase in sliding velocity for both of the tested materials. Gustafson [6] experimentally investigated the static and dynamic friction coefficients for 7 polymers types (Polyoxymethylene and Polyamides) by using sliding tribosystem consist in a steelball in cyclic sliding contact with plane polymer samples. For a normal load of 60 N and a steel ball having 8 mm diameter, Gustafson obtained various values both for static and dynamic friction coefficient with values between 0.05 to 0.5 as function of the polymer type. Barnea [7] experimentally investigated the friction between small cylindrical surfaces and artificial fingers realized from elastomer and evidenced that the friction behavior between cylinder and elastomer is a complex process.
including elastic deformations, sliding processes and elastic relaxation as a succession processes in a cyclic linear motion. Barnea [7] evidenced the “butterfly” configuration for the dependence curve between friction force and sliding distance. Rusu et a. [8] evidenced the similar “butterfly” configuration between steel and aluminum cylinder in contact with a plane PDMS elastomer.

In the present paper the authors investigated the friction behaviour of 9 different types of polyuretanes realized by “Petru Poni” Institute of Macromolecular Chemistry Iași as solution for antifriction layers deposed on metallic surfaces. The authors used an original tribostest system consist in sliding of a steel roller on a plane polyuretan sample by using the CETR UMT 2 Tribometer from Mechanical Engineering Faculty of Iași. Tribological properties for polymers are experimentally determined at normal loads between 1N and 15 N for sliding velocity of 1mm/s, 5mm/s and 10 mm/s in a linear cyclic motion. The friction force and friction coefficient was measured in dry and lubricated conditions and were compared for all types of polyuretanes.

2. Experimental methodology and testing equipment

Materials

The “Petru Poni” Institute of Macromolecular Chemistry from Iași realized the tested polyurethanes. It was prepared by the reaction of dibenzyl diisocyanate with poly(ethylene adipate) glycol, using diethylene glycol and trimethylol propane as chain extender and crosslinker in toluene-dichloromethane solution. In the Table 1 are presented the specimen codes and the chemical composition for the 8 types of polyuretanes.

Table 1. The chemical composition for polyurethanes used in the tribological tests

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>Specimen dimensions (width x thickness) [mm]</th>
<th>Polyurethane composition</th>
<th>DBDI mmol</th>
<th>PEA mmol</th>
<th>DEG mmol</th>
<th>TMP mmol</th>
<th>P1715 mmol</th>
<th>TEOS mmol</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1716 A</td>
<td>8 x 0.6</td>
<td></td>
<td>17</td>
<td>5</td>
<td>6.6</td>
<td>1.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1716 B</td>
<td>5 x 0.7</td>
<td></td>
<td>17</td>
<td>5</td>
<td>6.6</td>
<td>1.8</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>P1716 C</td>
<td>5 x 0.7</td>
<td></td>
<td>17.5</td>
<td>5</td>
<td>6.6</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P1716 E</td>
<td>5 x 0.3</td>
<td></td>
<td>18.1</td>
<td>5</td>
<td>6.6</td>
<td>1.8</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>P1716 H</td>
<td>8 x 0.5</td>
<td></td>
<td>21.6</td>
<td>5</td>
<td>6.6</td>
<td>1.8</td>
<td>2.7</td>
<td>-</td>
</tr>
<tr>
<td>P1716 I</td>
<td>5 x 0.2</td>
<td></td>
<td>21</td>
<td>5</td>
<td>6.6</td>
<td>1.8</td>
<td>1.8</td>
<td>5</td>
</tr>
<tr>
<td>P1716 M</td>
<td>5 x 0.5</td>
<td></td>
<td>17</td>
<td>5</td>
<td>6.9</td>
<td>-</td>
<td>1.8</td>
<td>10</td>
</tr>
<tr>
<td>P1716 R2</td>
<td>8 x 0.5</td>
<td></td>
<td>17</td>
<td>5</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*The dimensions are valid for the samples that were cut in strap form to be used in friction experiments.

3. Mechanical tests

The specimens were cut in dumbbell shaped form according to the standard DIN 53504-S3A:1994 and subjected to uniaxial tension until broken. The measurements were run at an extension rate of 50 mm/min in RT conditions. The elastic tangent modulus (Young’s modulus) was calculated from the slope of stress-strain curve at small strains (up to 10%), where Hooke’s law is still valid. Details about the experimental setup and tests procedure can be found in Ref. [9]. Table 2 summarized the mechanical parameters from tensile test experiments for all specimens.

Table 2. Mechanical properties of polyurethanes from tensile tests

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Film thickness (mm)</th>
<th>Stress at break (MPa)</th>
<th>Elongation at break (%)</th>
<th>Young’s modulus E (calculated at 10% strain) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1716 A</td>
<td>0.45</td>
<td>29.64</td>
<td>635.64</td>
<td>25.27</td>
</tr>
<tr>
<td></td>
<td>0.425</td>
<td>14.17</td>
<td>430.74</td>
<td>23.67</td>
</tr>
<tr>
<td>P1716 B</td>
<td>0.658</td>
<td>21.33</td>
<td>846.84</td>
<td>6.83</td>
</tr>
<tr>
<td></td>
<td>0.692</td>
<td>10.98</td>
<td>690.08</td>
<td>5.81</td>
</tr>
<tr>
<td></td>
<td>0.623</td>
<td>18.72</td>
<td>829.55</td>
<td>7.37</td>
</tr>
<tr>
<td>P1716 C</td>
<td>0.48</td>
<td>24.91</td>
<td>254.123</td>
<td>37.48</td>
</tr>
<tr>
<td>P1716 E</td>
<td>0.272</td>
<td>22.93</td>
<td>391.73</td>
<td>84.34</td>
</tr>
<tr>
<td></td>
<td>0.278</td>
<td>20.08</td>
<td>399.09</td>
<td>82.68</td>
</tr>
<tr>
<td>P1716 H</td>
<td>0.209</td>
<td>17.42</td>
<td>248.37</td>
<td>91.13</td>
</tr>
<tr>
<td></td>
<td>0.205</td>
<td>14.40</td>
<td>178.45</td>
<td>90.66</td>
</tr>
<tr>
<td>P1716 I</td>
<td>0.238</td>
<td>26.47</td>
<td>436.70</td>
<td>86.52</td>
</tr>
<tr>
<td></td>
<td>0.24</td>
<td>23.36</td>
<td>388.03</td>
<td>83.58</td>
</tr>
<tr>
<td>P1716 M</td>
<td>0.433</td>
<td>10.30</td>
<td>220.08</td>
<td>47.05</td>
</tr>
<tr>
<td></td>
<td>0.446</td>
<td>9.26</td>
<td>203.73</td>
<td>43.9</td>
</tr>
<tr>
<td>P1716 R2</td>
<td>0.52</td>
<td>2.26</td>
<td>22.16</td>
<td>15</td>
</tr>
</tbody>
</table>

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4. Tribological tests

The friction behaviour of polyurethane specimens was investigated using a steel cylinder sliding on a flat specimen. The method proposed by the authors has the advantage that maintains a constant contact pressure between the cylinder and polymer during the test, compared to other methods from literature such as pin-on-disc, ball-on-disc and disc-on-disc tribosystems [2,6], in which an important resistance due to the elastic deformation of polymer contribute to total friction force. The cylinder is a steel bearing roller with diameter of 7 mm, length of 14 mm and the surface roughness having $R_a = 0.066 \mu m$. The roller was fixed on the top of a pin that was attached to the force sensor of the Tribometer CETR UMT-2 as in Figure 1. The specimens look like a strap with the dimensions listed in the Table 1. They were glued on a metallic plane support and fixed on the linear table of the Tribometer.

![Figure 1: Experimental setup for friction measurements](image)

Friction measurements were performed by sliding the cylinder on polymer sample in the direction of cylinder axis that is perpendicular to the sample. The tests were made for normal loads between 1N and 15 N with sliding velocity of 1 mm/s, 5 mm/s and 10 mm/s. During the friction tests the cylinder is in permanent contact with polymer sample that has a cyclic movement in backward and foreword on a distance $Y$ of 4 mm in each direction. The tangential force ($F_t$), friction force ($F_f$), normal load ($F_z$), sliding velocity ($v$), time and distance ($Y$) are monitored and recorded by the soft of the Tribometer. Friction coefficient was measured in dry and lubricated condition at room temperature.

For measurements in lubricated condition the authors used a synthetic grease SSX having base oil viscosity of 1000 mm²/s at 20°C.

The influence of load, velocity and lubricant on friction coefficient was investigated for all samples.

5. Results and Discussions

An example of the variation of friction force ($F_t$) and friction coefficient (COF) with time in dry condition is illustrated in figure 2 for the polyurethane P1716 B. The cyclic movements of linear table on Y direction are also showed in figure 2. It can be observed that at the beginning of movement there is a peak value in the curve of friction force that corresponds to a static friction coefficient. Once the sliding distance reach 4 mm the direction is changed and the friction force shows again a peak. During the sliding of the roller on the polyurethane sample the friction coefficient is almost constant around 0.05 for a linear speed of 1mm/s.

![Figure 2: Variation of friction force, friction coefficient and distance with time at $F_z=10 N$ and $v=1 mm/s$ for P1716 B](image)
Characterization of Some Types of Polymers by Friction Behaviour

To evidence the different friction behaviour of all polyurethane specimens, in Figure 3 are presented the variations of the friction force $F_f$ obtained for a normal load $F_z = 10$ N and linear speed of $1$ mm/s.

It can be observed different friction force variations for the polyurethane specimens. Following friction behaviors of the polyurethanes can be observed:

(i) Polyurethanes with low and constant friction force on linear stroke $Y$ as P1716 A and P1716 B types. It can be considered that the dominant tribological process is the adhesion friction between roller and sample and elastic deformation on motion direction can be neglected.

(ii) Polyurethanes with linear increasing of the friction force from the point of the start of motion to the end of the stroke as: P1716 I and P1716 M. The increasing of the friction force according to increasing of the distance from the start point it can be considered as a supplementary force caused by the elastic deformation of the polyethylene in the direction of the motion.

(iii) Polyurethanes with relative constant value of friction force but with high value as P1716 H.

(iv) Polyurethanes with large variation of the friction force during the sliding process as P1716 E. It can be observed important decreasing and increasing of the friction force where we consider that the friction is dominate by the visco elastic behavior of the polyurethane.

(v) Polyurethane with high and sinusoidal values of friction force during the sliding process as P1716 C. For this type of polyurethane as a result of high adhesion forces in contact with the steel roller can be developed the stick–slip process.

By using the new diagrams having the variation of the friction coefficient COF on the sliding distance $Y$ it can be evidence more realistic the friction behavior of the polyurethanes. So, in Figure 4 are presented the most representatives diagrams COF- $Y$ obtained in dry conditions for normal load $F_z = 10$ N and linear speed $v = 5$ mm/s.

Figure 3: The variation of friction force with time for all samples tested at $F_z=10$ N and $v=1$ mm/s

Figure 4: The variation of friction coefficient COF on the sliding distance $Y$ for $F_z = 10$ N and linear speed $v=1$ mm/s
From Figure 4 it can be observed that the probe P1716 B realize a low constant dynamic friction coefficient on the distance Y both in one direction and in opposite direction, excepting the start points at 0 mm and at 4 mm when appears picks as a result of static friction coefficients. The next probe P1716 C have an increases of the friction coefficient from the start point to the end point at Y = 4 mm. More complex is the variation of the friction coefficient on the distance Y for the probe P1716 E when it can be observed an increasing of the friction coefficient from the start point to 3 mm, after that follows a small decreasing to the end of the distance Y. We suppose that the elastic component of the friction force is dominant in contrast with the adhesive force. Also, it is not easy to established what is the real friction coefficient caused only by sliding process between roller and polyurethane P1716 E if his variation is between 0.02 to 0.11 on the distance of 4 mm.

Another complex behavior in friction process it can be observed for the probe P1716 R2 where, as is presented in Figure 4, the friction coefficient variation in one direction is higher that the friction coefficient in opposite direction. Our opinion is that during the sliding process an internal friction in the polyurethane P1716 R2 is developed as result of a “hysteresis” process.

**Influence of the normal load and linear speed on friction coefficient for probe P1716 B in dry conditions**

Because the polyurethane P1716 B have a constant value of friction coefficient during the all distance Y, the researchers was continued to determine the influence of the normal load, linear speed and the presence of lubricant on the friction coefficient for this probe.

In Figure 5 is presented the influence of the normal load Fz on the friction coefficient for polyurethane P1716 B for sliding speed v = 1 mm/s. It can be observed that friction coefficient decreases with normal load from COF = (0.14 – 0.15) for Fz=1 N to COF =0.04 for Fz=15 N.

The tendency of the decreases the friction coefficient by increasing the normal load is observed both at v = 5 mm/s and v = 10 mm/s. So, the variations of the friction coefficient with the normal load for linear speed v =5 mm/s are presented in Figure 6 and for the linear speed of 10mm/s are presented in Figure 7.

From figure 6 and 7 it can be observe that by increasing of the linear speed in dry conditions the friction coefficient COF for polyurethane P1716 B increases. Also, it can observe that for linear speed of 5 mm/s and
especially for linear speed of 10 mm/s at low load (Fz = 1N) the variation of the friction coefficient along of the distance Y have high variations with values between 0.15 to 0.30. By increasing of the normal load the variation of the friction coefficient is reduced. By curve fitting the variations of the friction coefficient with the ratio $F_z/F_{z,max}$ where $F_{z,max} = 15$ N, it can be obtained following empirical equations for normal load dependence:

$$
\mu(F_z) = 0.044 \left( \frac{F_z}{F_{z,max}} \right)^{0.457} \quad v = 1 \text{mm/s}
$$
$$
\mu(F_z) = 0.047 \left( \frac{F_z}{F_{z,max}} \right)^{0.327} \quad v = 5 \text{ mm/s}
$$
$$
\mu(F_z) = 0.103 \left( \frac{F_z}{F_{z,max}} \right)^{0.332} \quad v = 10 \text{ mm/s}
$$

Influence of the lubricant on friction coefficient for probe P1716 B

To determine the influence of the lubricant on the friction between steel roller and polyuretan synthetic grease SSX was used in small quantity. The presence of the synthetic grease SSX leads to important decreases of the friction coefficient. In figure 9 are presented the variations of the friction coefficient for dry and lubricated conditions for polyurethane P1716B loaded with Fz = 5N and tested at linear speed of 5 mm/s and 10 mm/s respectively.

![Figure 8: The variation of friction coefficient with normal load and linear speed for P1716 B](image)

![Figure 9: The variation of friction coefficient in dry and lubricated conditions for P1716 B](image)

For both sliding speed values the presence of the grease can reduce the friction coefficient to 0.02 – 0.03, that means very good values for antifriction conditions. Also, this type of polyurethane has a very good adherence of the grease layers that means a constant friction coefficient for the cyclic sliding of the roller over the sample.

6. Conclusions

In this study, the authors used a new methodology to investigate the friction behaviour of some polymers. To eliminate the contribution of elastic deformation on the total friction force, the authors used a cylinder-plate tribosystem that have the advantage to maintain a
constant contact pressure and deformation during the
tests. The cylinder slid on a strip of polyurethane in dry
and lubricated condition at room temperature. The
friction force and friction coefficient are investigated
according to normal load between 1N and 15 N and
sliding speed between 1mm/s and 10 mm/s.
We investigated the friction forces and friction
coefficients for 8 polyurethane probes realized by
“Petru Poni” Institute of Macromolecular Chemistry
from Iași. Important differences refer to the friction
behavior between the polyurethane probes have been
evidenced:
(i) Some polyurethanes realize in dry conditions a low
and constant friction coefficient along the entire sliding
distance (0.05 –0.1), that means good applications as
deposed layers for antifriction tribosystems;
(ii) Other polyurethanes realize in dry conditions high
friction coefficient (higher that 0.1) that means poor
antifriction behaviour. Also, other polyurethanes have
high variations of the friction force and friction
coefficient during the sliding process. As a result of a
pronounced visco elastic behavior.
By experiments was established that the polyurethane
P1716 B have a very good antifriction characteristic
and for this polyurethane were realized more tests to
evidence the influence of the normal load, sliding speed
and presence of lubricant on the friction coefficient.
Was evidenced that in dry condition, friction
coefficient showed to decrease with the increase of
normal load and increases with increases the sliding
speed. Empirical equations for P1716 B polyurethane
probe have been established.
Also, the friction coefficient for P1716 B polyurethane
dramatically decreases in lubricated conditions.

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