Friction and Wear of Polybutylene Terephthalate Against Steel in Block-on-ring-tests

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The paper presents results on friction and wear, obtained from testing polybutylene terephthalate (PBT) against steel in a block-on-ring tribotester, for dry sliding. There were identified particular processes characterizing the friction couple and the test conditions. Tests were done for three sliding speeds: 0.25 m/s, 0.50 m/s and 0.75 m/s and for five normally applied loads: 1.0 N, 2.5 N, 5.0 N, 10.0 N and 20.0 N. The sliding distance was 7500 m. For comparing reason, there were also done tests for blocks made of PTFE. For PBT-steel couple, the friction coefficient remains in an acceptable range for forces above 2.5 N but it has higher value at the lowest tested values of the force (F=1.0...2.5 N). For evaluating the wear of PBT blocks, there was plotted a wear map using as wear parameter the linear wear intensity as a function of sliding speed and normal force. On this map, there were identified two zones with low values. There were indentified particular processes taking place on the PBT blocks and the steel rings that explain the good tribological behavior of this friction couple. The results of these tests recommend PBT for tribological applications that would function under similar dry regimes.

Keywords: friction coefficient, wear, PBT, dry sliding, block-on-ring

Sinha and Briscoe [27], in their "Polymer Tribology" - a very comprehensive and up-to date book about processes related to friction and wear of polymers and their composites, did not included the polybutylene terephthalate (PBT) in any comment, but a web search gives data for this product related to tribological applications [36-39]. This could be explained both by the rapid progress in manufacturing parts made of PBT and by the particular behavior of this polymer when it is rubbed against itself or against steel [8, 38]. In [27, 28], even if Stachowiak and Batchelor did not mentioned PBT, they described the model of the "insular" transfer that the authors of this paper discovered to be as appropriate for rubbing PBT against steel.

Research of PBT behavior has been developed due to its market share among polymeric materials. At the end of the XXth century, the Western European market demands 90 000 tons per year, the United States about 140 000 tons per year and Japan over 60 000 tons per year [3]. One of the advantages of this polymer is that it could be made using the same plant as employed for the manufacture of the much largely yet used material PET [3, 4]. However, the market for injection molded PBT parts is much greater than that for injection molded PET parts. The use of PBT as an engineering material is more a consequence of a balance of good properties rather than of a few outstanding ones.

As the producers point out in their catalogues [36-39], electrical and automotive industries and a variety of other products benefit from the desirable property combination and moldability of PBT and its composites. The increasing interest in testing PBT is required by its fields of applications (fig. 1) [3], the tribological aspects being very important especially for business machinery applications and automotive industry.

As chemical structure, PBT is included in the thermoplastic polyester resins' family [3, 4, 16] that excels with a combination of: dimensional stability, stiffness and strength, creep resistance, dielectric properties, impact resistance, long-term heat resistance, resistance to solvents and lubricants. "When DuPont made its big move into PBT in 1993, we knew you didt need another source of me-too resins" [37]. The composites with PBT matrix and the polymeric blends with PBT exhibit interesting tribological and mechanical properties [1, 9, 14, 17, 19, 24].

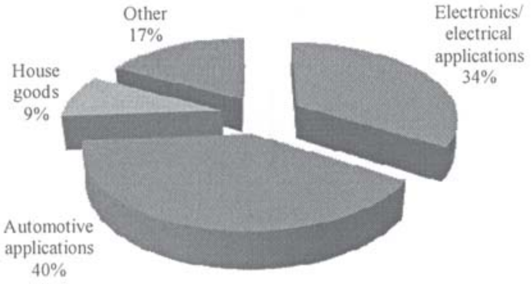

Fig. 1. The fields of applications for PBT and materials based on PBT [3]

Experimental part

Testing methodology

The friction and wear behavior of the PBT sliding against steel was evaluated with the help of a Universal Micro-Tribometer UMT-2 and a block-on-ring tribotester. The geometry of the frictional couple is given in figure 2.

The polymeric blocks are prisms of 16.5 mm × 10 mm × 4 mm and they were obtained by injection at ICEFS Savinesti, Romania, according to the specifications of the producer [35] and [12] from traction samples, cutting the blocks from the middle parallel zone of them. The PBT grade was Crastin® 6130 NC010, an unreinforced, medium high viscosity polybutylene terephthalate resin for extrusion and injection molding [40]. Some of the properties of this grade of PBT are given in table 1.

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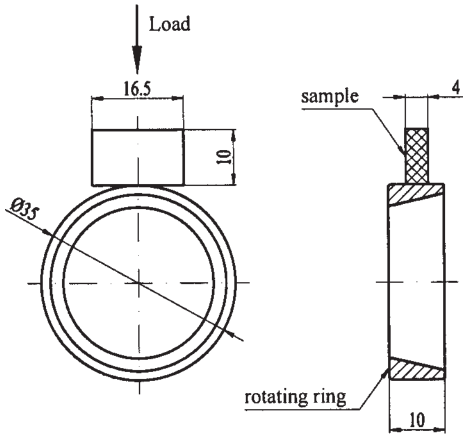


Fig. 2. The tribotester block-on-ring

Table 1
MECHANICAL PROPERTIES OF PBT GRADE
CRASTIN® 6130 NC010 [3, 4, 40]

Property	Value
Density, kg/m^3	1300
Yield Stress, MPa	59
Strain at Break (50 mm/min), %	110
Tensile Modulus, MPa	2600
Shore hardness, D	90...95
Maximum continuous temperature, °C	80...140
Melting Temperature, at 10°C/min, °C	225
Deflection Temperature, °C	
0.45 MPa, annealed	180
1.80 MPa, annealed	60

Table 2
CHEMICAL COMPOSITION OF THE 100CR6 STEEL RINGS (%wt)

C	Si	Mn	P	S	Cr	Ni	Cu
0.90-1.05	0.15-0.35	0.25-0.45	≤0.030	≤0.025	1.35-1.65	≤0.30	≤0.30

From a traction sample with length of 150 mm and cross section in the parallel middle zone of 10 mm x 4 mm (according to ISO 527-2 Plastics. Determination of tensile properties. Part 2: Test conditions for molding and extrusion plastics), 4 blocks could be cut. All obtained traction samples have been submitted to an annealing treatment after molding, as recommended by the producer [35], before cutting the blocks. The rings of ∅ 35 mm × 10 mm were made of 100Cr6 steel (60-62 HRC, Ra=0.1...0.3 μm). The chemical composition of the ring steel grade is given in table 2. The ring is the external ring of a tapered rolling bearing type 30202.

The tribotester performance for maintaining a very narrow range for the normally applied load was very good (less than ±5%), even under wear debris generation regime.

In the reference books [5, 20, 21, 27] it is underlined that the friction and wear processes are better related to the normal load or to the maximum pressure in the contact, especially for theoretically linear contact. For block-on-ring tests, there are given information about the contact loading in very different terms [21, 26, 31-34]. The maximum pressure calculated for the theoretically line contact could be drastically different in the actual contact than those calculated with Hertz formulas, especially when it is used a polymeric or a polymeric composite block because it changes its contact shape, adapting it to the hard ring by elasto-plastic deformation and polymeric material loss. The average pressure calculated with the final area of the worn surface (as a plane area of the wear track or as a spatial area of the wear track) is an adequate expression of contact loading but it has to be mentioned and kept the calculated method for comparing materials. Often, due to wear and plastic deformation, the initially calculated value of the maximum pressure is diminishing for the friction couple including a polymer block. Samyn [25] reported such a decrease for POM and PET on a steel ring. It is this reduction of the maximum pressure in contact that makes the polymeric parts to last under high loads.

After consulting the literature [2, 13, 15, 18, 21, 23, 30-34] and taking into account the team experience [6, 7] and possible applications of PBT, there were selected the following test parameters: for the sliding speed: v=0.25 m/s, 0.50 m/s and 0.75 m/s, for the applied load: F=1.0 N, 2.5 N, 5.0 N, 10.0 N, 20.0 N; the sliding distance was L=7500 m for each test done at room temperature and in a laboratory environment.

Results and discussions

Taking into account Czichosh's stages for the evolution of the friction coefficient [5], PBT seems to have a very short stage of increasing (about 200…250 m) and then the value is kept in a narrow range (fig. 3). At v=0.75 m/s, the evolutions of the friction coefficient are similar, with values around 0.2, meaning that the load influences less the friction for this sliding speed. These tests done at v=0.75 m/s exhibit the same type of superficial mechanisms. Analyzing figures 8a and 9b, the wear particles seem to be similar in dimensions and the polymer surface exhibits only some micro wear tracks, the polymer looking soften when the sliding speed is increased at v=0.75 m/s.

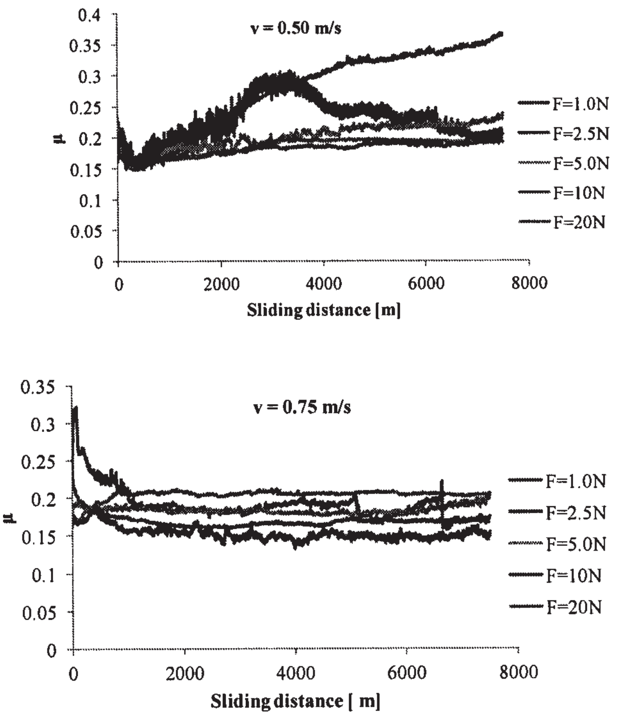


Fig. 3. The evolution of friction coefficient for two of the tested sliding speeds, for a sliding distance of 7500 m

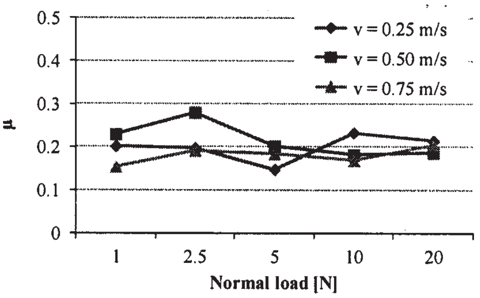


Fig. 4. The average values of the friction coefficient, μ

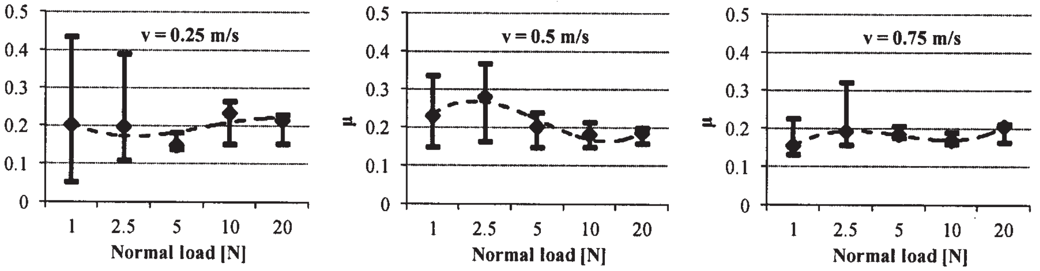


Fig. 5. The scattering intervals and the average values for the friction coefficient, μ, as a function of the normal load, F, for each tested sliding speed, v

An increase of the friction coefficient for F=2.5 N and v=0.5 m/s at more than μ=0.3 may signify the intensification of the abrasive component of wear. A further increase of the sliding speed to 0.75 m/s may generate a viscous friction that reduces the friction coefficient but after 3000...3500 m the value was also increasing. A too low load (F=1.0...2.5 N) does not compact the superficial layer of the polymer and this is more easily torn off from the block. The variation of the friction coefficient could be explained by an intense process of wear debris generation: the polymer at the surface is too softened and it is easy to be deformed and detached, causing a large variation of the friction coefficient.

At higher speed, the influence of load on the evolution of the friction coefficient is insignificant (fig. 4). This ability of PBT to be almost insensitive to load for a certain range of sliding speeds could be exploited in order to increase productivity of the entire system containing PBT parts. When plotting the average value of the friction coefficient against the normal force, this tendency of not depending on the sliding speed is obvious for v=0.75 m/s (fig. 4). The average value was calculated for each test as the average of all recorded values during a test.

The narrow range of the friction coefficient for v=0.75 m/s could reflect the development of a similar friction mechanism between PBT and steel ring, at all tested loads.

The SEM images (figs. 10 and 11) show a similar quality of the ring surfaces for different sliding speeds and loads. The wear debris for the higher speed are bigger and exhibit darken color, this could be the effect of thermal degradation of PBT [3], as exposed in very thin bands or micro-bulges of the wear debris.

High oscillations of the friction coefficient for the friction couples involving a polymeric element (made of either neat polymer or composites) have been reported even from ’70s in a NASA report [13], for three tested polymers; there was used a tribotester ball (made of polymer) and a disk made of hard steel and the average of the friction coefficient was for many tests conditions around 0.6, with big oscillations towards even 1.0. Then, Li [18] and Akiyama et al. [1] also have reported high average values and big oscillations for low speed and low load. From figures 3 and 5, one may notice that low speeds and forces generated large scattering intervals for the values of the friction coefficient characterizing the couple PBT-steel and this tendency is maintained for repeated tests under the same conditions. When the normal friction and the sliding speed are increased, the average value of the friction coefficient is lowered just a little, but the scattering intervals are narrower (μ=0.14...0.23).

From figure 5, it is obvious that even if the average value is low for all tests, the scattering intervals differ; at low loads (F=1.0...2.5 N), this interval is quite large, especially for the lowest tested speed, v=0.25 m/s. The dash lines in figure 5 were obtained by polynomial interpolation of third order.

The design problem is if the actual system will maintain its reliability in an acceptable range when the polymeric part is subject to the actual functioning conditions. This is why the approach between the polymeric block and the steel ring, ΔZ [μm], could be a good parameter in evaluating the wear, even if it also includes thermal expansions of both elements and the misalignment influences (very small on the new-generation of tribotesters as UMT-2). A value of ΔZ that could be as big as the maximum allowance for a bearing fit (it is not the only example that could be given) will not be allowed in practice. Thus, the block wear was expressed by the linear wear intensity, *WI*, calculated as

$$WI = \frac{\Delta Z}{F \cdot L} \ [\mu m/(N \cdot km)] \qquad (1)$$

where ΔZ [μm] is the approach between the block and the ring at the end of the test, F [N] is the normal force and L [km] is the sliding distance.

The technique for wear mapping could be useful for a systematic approach of the wear data, helping to establish a hierarchy of the tested materials and also to notice changes in the wear processes as induced by the variables [7, 11, 30].

On the linear wear intensity map presented in figure 6, one may notice two zones with higher values (red-yellow zones):

- at F=1.0 N, this wear parameter is kept high for v=0.5 m/s and v=0.75 m/s and it is decreasing only with 18% for v=0.25 m/s;
- between F=10.0 N and F=20.0 N and for the lowest tested sliding speed, the parameter is high on the mathemathically modelled wear map. The map was plotted with the help of MATLAB® soft, using a cubic interpolation.

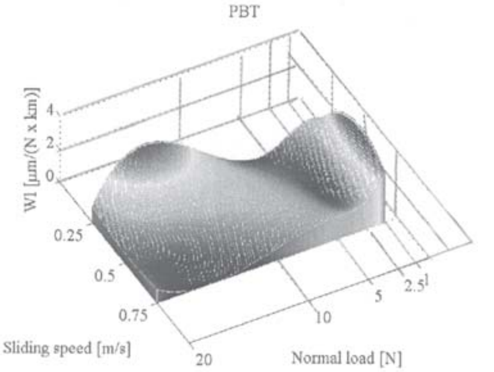


Fig. 6. The map of the linear wear intensity for PBT blocks as a function of the normal force and the sliding speed

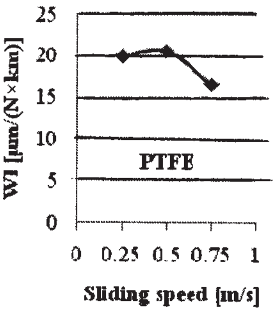
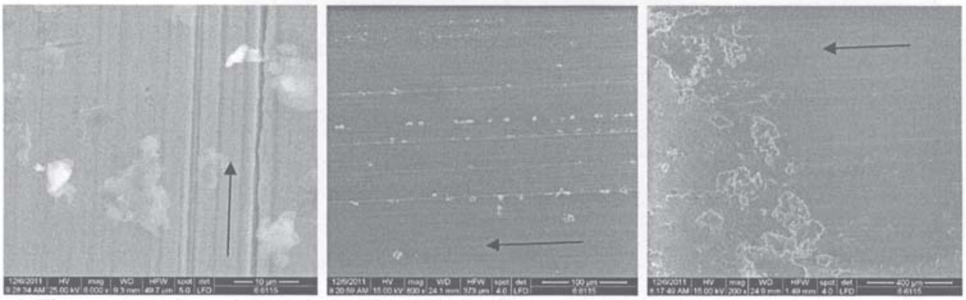


Fig. 7. The linear wear intensity for PTFE (tests done for F=5.0 N and L=7500 m)



a) The wear track on the steel ring, after a test mag. 6000 ×

b) The wear track on the PBT block mag. 800 ×

c) PBT wear particles at the exit zone of the block contact mag. 200 ×

Fig. 8. SEM images after the test with v=0.25 m/s and F=5.0 N (Arrows indicate the sliding direction)

There are two zones with lower values. One for the forces 2.5...5.0 N and the cause could be the decreasing of the abrasive component of the wear, as the higher force compressing the tribolayers does not allow for detaching bigger particles from the polymeric blocks. The second zone of low wear parameter is in the range of 10.0 N...20.0 N and sliding speeds higher than 0.5 m/s. Here, the reason for having such good results may be the softening process of the polymer due to heat power generation in dry friction, as aslo presented in [27-29]. As SEM images reveal, the polymer does not transfer in an intensive manner on the steel ring (as it happens with other polymers under such test conditions, especially with PTFE and PA [6, 10, 22, 30]) and the hard asperities only deform the soften layer (these deformations could include elastic and plastic components).

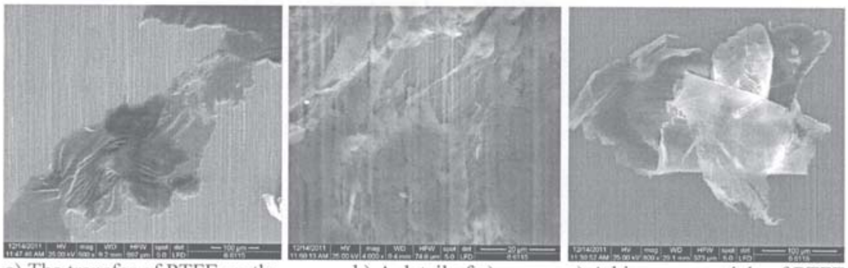
There were good results for PBT sliding against steel but in order to have reliable comparative results, the authors did the same tests for blocks made of PTFE, for F=5 N, for all tested sliding speeds. As shown in figure 7, the linear wear intensity for PTFE is almost 20 times bigger than that obtained for PBT under the same testing conditions. At v=0.75 m/s, this parameter decreases for the blocks made of PTFE and it could be explained by diminishing the contribution of the abrasive component and by a more stable transfer in time of PTFE; due to the particular regime, the transferred film (almost continuous) is not removed so fast as it happens at lower speeds [5, 26, 27, 30].

As comparing to other polymers rubbed against steel, the mechanisms developed during friction of PBT have noticeable differences. There is less transfer film (appreciated both by volume and by covered areas) as compared to the transfer films obtained with other polymers [6, 7, 22, 30]. Rare and small-volume wear particles of PBT are “trapped” into the steel topography (fig. 8a) or mechanically “bonded” to the polymeric surface (fig. 11b). PTFE has the tendency of adhering its detached bands (or micro-flakes) (figs. 9a and 9b) and the hard asperities mechanically detach PTFE in a more intense process (figure 9c presents a typical wear particle of PTFE). There are wear tracks in the sliding direction, but these seem to be the result of the plastic deformations rather than micro-cutting.

Figures 8a and 9 give SEM images of the steel ring after being rubbed against PBT and PTFE, respectively, in order to point out the difference in their wear mechanisms. Figure 9b shows small drawn fibers and transferred PTFE. There are smaller particles re-attached to the already adhered ones.

Many of the wear debris are thrown out from the contact near the wear track generated on the steel ring and some of them near the contact exit on the polymeric block (fig. 8c). These wear debris consist especially of polymeric material (change of the polymer color reflect its thermal degradation [3, 19]) and very rarely there were detected small steel debris, as the EDX analysis reveals. Figure 10 presents an EDX analysis before and after a test, for the steel ring, pointing out the “insular” transfer of PBT. The EDX analysis in figure 10d is done for the square area in the centre of the SEM image. Studying the wear tracks formed on the steel rings, the authors noticed that PBT does not transfer as an almost “continuous” film (figures 9a and 9b), as reported for PTFE in [5, 10, 34].

The wear particles are rare and of smaller volumes as compared to that obtained with PTFE (see the scale in figure 9c, which presents a typically wear debris of PTFE, and compare to the scale in figure 8a), rolled and flattened by successive passes through the contact. This type of wear debris could explain the friction coefficient oscillations during the test and the higher values for the linear wear intensity.

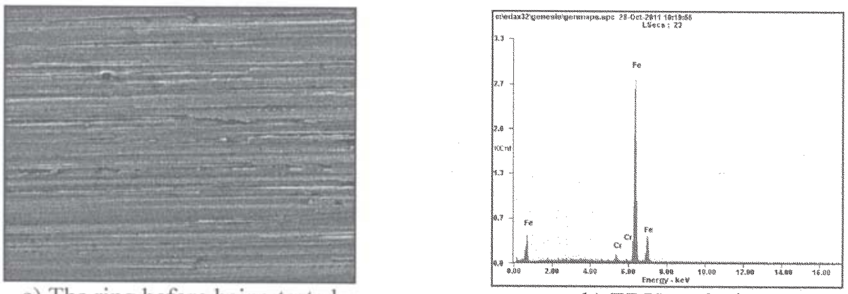


a) The transfer of PTFE on the steel ring (mag. 500 ×)

b) A detail of a) (mag. 4000 ×)

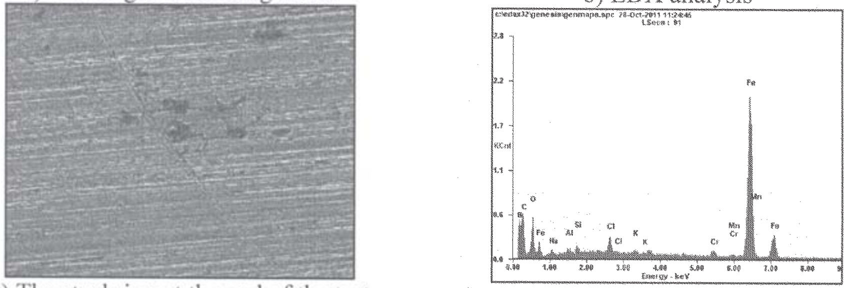
c) A big wear particle of PTFE on the steel ring (mag. 800 ×)

Fig. 9. SEM images of the worn surfaces for tests done with PTFE blocks, at F=5 N and v=0.75 m/s, for L=7500 m



a) The ring before being tested

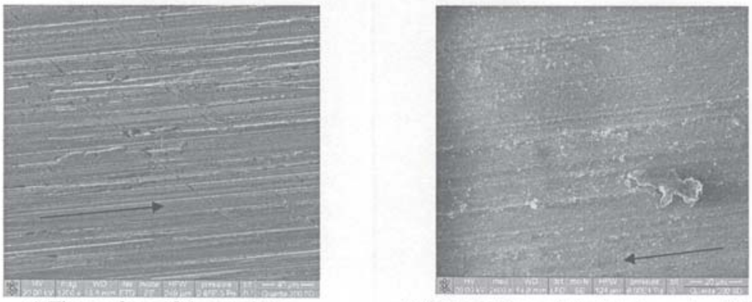
b) EDX analysis



c) The steel ring at the end of the test

d) EDX analysis for the square area in c)

Fig. 10. A prove of non-uniform polymer transfer on the steel ring Test conditions: v=0.75 m/s, F=5 N, L=7500 m



a) The surface of the steel ring (mag. 1200 ×)

b) The surface of the block made of PBT (mag. 2400 ×)

Fig. 11. SEM images after the test done at F=5 N, v=0,75 m/s, L=7500 m (arrows indicate the sliding direction)

Conclusions

The couple PBT – steel may be recommended for tribosystems with similar regimes as those used for this set of tests, that is sliding speeds of 0.25...0.75 m/s and normally applied loads of 5.0...20.0 N.

A synthetic presentation of the friction coefficient (fig. 12) points out that, except for low loads (F=1.0...2.5 N), PBT against steel in theoretically linear contact (as in block-on-ring tribotester) has a good friction coefficient (a low average value of 0.15...0.2 and narrow scattering intervals). Based on these results, it could be a reliable challenger for replacing PTFE parts that would have a higher wear under similar conditions if PBT fulfills the other requirements of the application (chemical and thermal resistance).

For evaluating the wear of PBT blocks there was plotted a wear map, using the linear wear intensity as a function of sliding speed and normal force. On this map (see figure 6), there were identified two zones with low values, one

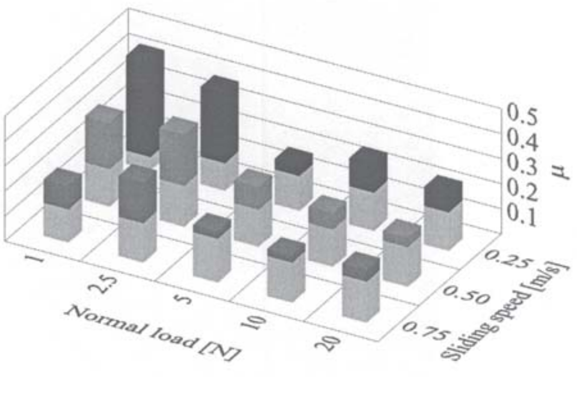


Fig. 12. The intervals for the friction coefficient, μ, depending on the normally applied load and the sliding speed. Each colored column represents the interval of the friction coefficient for a test characterized by (F, v). The grey column is drawn only for a clear view of its position in the plane (F, v)

for loads around F=5N at all tested speeds and one for higher speeds and loads of 10...20N.

There were indentified the particular processes taking place on the PBT blocks and on the steel rings explaining the good tribological behavior of this friction couple.

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