INFLUENCE OF ARAMID FIBERS ON TRIBOLOGICAL BEHAVIOR OF PBT

Mihail Botan¹, Constantin Georgescu¹, George Catalin Cristea¹, Lorena Deleanu(*)
¹Faculty of Engineering, “Dunarea de Jos” University of Galati, Galati, Romania
(*)Email: lorena.deleanu@ugal.ro

ABSTRACT
This work presents the tribological behavior of PBT (polybutylene terephthalate) + 10% aramid fibers and PBT, when sliding against steel in dry regime in order to point out the influence of adding fibers. Tests were done on a block-on-ring tribotester, for normal loads of 5 ... 30 N and sliding speeds 0.25 ... 0.75 m/s, for a sliding distance of 5000 m. Based on the experimental data, the authors recommend the composite for functioning in the tested ranges for speed and force, as its wear and temperature in contact and friction coefficient are reduced as compared to polymer.

The wear maps plotted based on the experimental results help to rank the tested materials and to emphasize several advantages of the composite PBT and 10% wt short aramid fibers: it allows for decreasing the temperature in contact (as measured at a lateral point of the contact) with 5...10º C for the highest values of the testing parameters, but for low speed and load the difference in temperature is almost insensible to the block made of neat polymer; for the composite, wear is reduced almost twice for F = 15-30 N and all tested speed range; wear of the composite is less dependent on speed, recommending it for applications with variable regimes; the friction coefficient is only several percentages higher as compared to that obtained for the block made of PBT, except for high load and speed (v = 0.75 m/s and F = 30 N), when the friction coefficient increases to 0.32-0.36). The SEM images pointed out a very particular lumpy transfer, both for polymer and composite, meaning the leading factor is the matrix material (PBT).

Keywords: PBT, short aramid fibers, block-on-ring test, wear map, friction coefficient.

INTRODUCTION
Researches on polymers and polymeric composites are focused on improving their properties related to particular applications, including the tribological ones (Stachowiack, 2001), (Bahadur, 2009), (Samyn, 2009), (Briscoe, 1981), (Thorpe, 1986), (Wardle, 2000), (Besnea, 2014) (Bang, 2004), sensors and aerospace materials (Meguid, 2005).

Polymeric composites with short aramid fibers have become of interest in the research field in the last decade, both as friction and antifriction materials. For tribological applications, length/diameter ratio characterizing the aramid fibers introduced in polymeric composites varies from 20 to 550 µm (Dorigato, 2013). Composites with thermoplastic matrix are especially used for their low friction coefficient and higher wear resistance as compared to the neat polymer (Akbarian, 2008), (Arroyo, 2002), (Bijwe, 2006) (Zhu, 2010), (Tang, 2011). Materials with rigid resins as matrix were tested for applications like brakes (Kim, 2001), (Larsen, 2007), (Singh, 2015), (Xian, 2006). Shibulal added coated short aramid fibers in a thermoplastic elastomer (Shibulal, 2011) and Kashani added aramid fibers in an elastomer for
tires (Kashani, 2009). There are several restrictions in using aramid fibers as reinforcement in tribological applications: a technological one, caused by the difficulty of molding / processing mixture with relevant concentration of aramid fibers, the quality of the fiber dispersion, even under laboratory conditions, and the aramid fiber sensitivity in fluids containing water.

Thermoplastics polymers used as matrix in composites with short aramid fibers included PA (Botan, 2014), (Gordon, 2009), PP (Maity, 2008), (Arroyo, 2002), PTFE (Qiu, 2015), (Fung, 2005), PS (Mukherjee, 2006), PI (Li, 2009), (Zhao, 2013). Reports on tribology of PBT composites are few (Kim, 2001), (Larsen, 2007) (Georgescu, 2012) and further investigation on a mixture like PBT and fibers is necessary for better exploitation its unique set of properties.

Several studies make comparison among composites with same matrix but different fibers, including mixture of fibers. Zhao et al. [Zhao, 2013] evaluated friction and wear of polyimides reinforced with carbon, glass and aramid fibers, under dry sliding against sandpaper and steel, under three-body abrasive conditions. The best performance was exhibited by inorganic fiber composites due to the load sharing. Brittle glass fibers have not contributed to improve wear resistance under abrasive conditions, due to insufficient support from polyimide matrix.

Short aramid fibers in a polymeric matrix could improve wear of polymeric composites but tests are required in order to evaluate the particular mix of wear mechanisms and the contact durability under conditions of the future application. Dorigato and Fambri (Dorigato, 2013) used regenerated aramid fibers in PA12, pointing out the effect of fiber concentration in the range of 10...30%, after a synthetic review of mechanical and tribological behavior of composites with short aramid fibers, the conclusion being that wear could be improved when using these materials and their application could include either antifriction or friction tribosystems, depending on the matrix characteristics. Results with composites with PBT matrix are promising as concern wear and temperature in contact as compared, for instance, to PA (Botan, 2014), (Maftei, 2011), (Yu, 1994) (Tang, 2011), (Ioffe, 2011). Other fillers, like carbon fibers, clay (Hwang, 2010) were added in PBT for improving wear behavior.

Polybuthylene terephthalate is a polymer only recently used as matrix because of technological reasons in molding parts made of this material, including properties’ control with the help of thermal treatment. Thus, researches on composites with PBT matrix are few and the future studies will help to introduce it (as neat polymer or composites) in tribological and mechanical applications.

MATERIALS AND TESTING METHODOLOGY

The block-on-ring tribotester is often used for characterizing the tribological behavior of a pair of materials, especially when dealing with polymeric materials sliding against steel because of block simplicity and high accuracy of the rolling bearing external ring, characterized by a high quality of surface texture and steel structure. The variables could be the sliding distance (L), the block material, the specific load (W), the speed (v) and, if the tribometer has a controlled enclosure, temperature and composition of the environment. Also, it is easy to compare dry and lubricated regimes.

This study deals with a composite with matrix made of PBT (grade Crastin 6130 NC010 – DuPont) and 10% wt short aramid fibers (Twaron D1088, 250 µm average length, supplied by Teijin). The material code is PBX in all figures. For technological reason, the composite contains 1% wt polyamide 6 (grade Relamid, produced by ICEFS) and 1% wt black carbon.
Samples were obtained by molding at Research Institute for Synthetic Fibers Savinesti (ICEFS) Romania and they were heat treated.

Table 5 - Studies on block-on-ring tribotester

<table>
<thead>
<tr>
<th>Authors, year</th>
<th>Block material, Matrix/ fillers</th>
<th>Test parameters (dry regime)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Li, 2007)</td>
<td>PTFE and PI</td>
<td>L [m]</td>
</tr>
<tr>
<td>(Georgescu, 2012)</td>
<td>PBT/ glass bead, PTFE</td>
<td>5000, 7500, 1000</td>
</tr>
<tr>
<td>(Wannasri, 2009)</td>
<td>UHMWPE/ carbon nanotubes</td>
<td>3840</td>
</tr>
<tr>
<td>(Qiao, 2007)</td>
<td>PEEK/ Al2O3</td>
<td>3000</td>
</tr>
<tr>
<td>(Jia, 2005)</td>
<td>PI, PEEK /carbon fibers</td>
<td>3000</td>
</tr>
<tr>
<td>(Cong, 2008)</td>
<td>PA</td>
<td>3000</td>
</tr>
<tr>
<td>(Zheng, 2007)</td>
<td>PA6/ braided carbon fiber</td>
<td>1500</td>
</tr>
</tbody>
</table>

Experimental results are difficult to be compared, but qualitative evaluation was taken into consideration for this work (Table 1). The authors, based on (Maftei, 2011), (Georgescu, 2012), considered that 5000 m was reliable for pointing out a stable friction and wear rate, for the tested materials and the test parameter ranges (v = 0.25 m/s, 0.5 m/s and 0.75 m/s, W = 1.25 N/mm, 2.5 N/mm, 3.75 N/mm and 7.5 N/mm).

The geometry of the tribotester is given in Fig. 1. The blocks (16.5 mm × 10 mm × 4 mm) were cut with the help of a water jet machine, from the mold plates. Figure 2 presents the way of cutting the blocks from a mold plate; the molding nozzle is positioned in the centre of the plate. Selected zone have a good dispersion of fibers and central and peripheral zone are excluded because of high probability of having a non-uniform dispersion of aramid fibers.

The blocks were dried in an oven immediately after being cut. The other triboelement was the external ring of the tapered rolling bearing KBS 30202, made of steel grade DIN 100Cr6 (see Table 2), with 60-62 HRC and Ra = 0.8 µm on the exterior surface.

Taking into account that an average stress on the contact is not relevant for evaluating such a contact between two materials with very different mechanical properties, the maximum pressure depending on the elasto-plastic behavior of the polymeric block. In order to compare
some results from literature for block-on-ring tests (see Table 1), the authors calculated a linear load, this type of contact better characterizing by the linear load:

$$ W = \frac{F}{b} \text{ [N/mm]} $$

(1)

where $F$ is the normal load, in N, $b$ – the theoretical length of the contact, in [mm].

| Chemical composition of steel grade 100Cr6 (DIN 17230) (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 |

RESULTS AND CONCLUSIONS

The values for the friction coefficient are good for both tested materials (see Fig. 3 and Fig. 4), with lower values for the polymer as compared to the composite, for normal loads of 5–15 N, but at F=30 N, this parameter is in a close range for both materials.

![Fig. 3 - Evolution of friction coefficient in time, for different loads and sliding speeds](image-url)
The temperature on the lateral side was monitored with the help of a thermographic camera and the maximum recorded values are points on the maps in Fig. 9. An engineer will be interested in having materials with low temperature in functioning and low influence of load and speed on this temperature.

**PROCESSES IN THE SUPERFICIAL LAYERS**

Transfer processes are very important in selecting the pair of materials involved in a tribological applications, especially when dealing with polymers and their composites (Stachowiak, 2001), (Czicosh, 2009). Their generation and evolution influence friction and wear. Transfer processes have to be studied on both triboelements. PBT and its composites (Georgescu, 2012) have a very particular transfer process, which differenciate their tribological behavior, as compared to other polymeric composites on steel. SEM images reveal several aspects due to the combination PBT – aramid fibers: adhesion wear (Fig. 8a, c and f), abrasive wear (Fig. 5), transfer film (Fig. 8a, b, c and e), fiber degradation (Fig. 7, Fig. 8f), wear debris generation and evolution (Fig. 8b and d).

SEM investigations proved that (Cong, 2008) wear debris shapes are strongly dependent on polymer or composite: for instance, PA46 formed two kinds of wear debris with different morphology: belt-like and spiral rod-like wear debris. The main wear mechanisms of PA46 against steel were adhesive wear and melting flow. The melting flow was not visible on PBT block due to its better thermal characteristics (Figures 5 and 7).

![Fig. 4 - The influence of normal load and sliding speed on the average and the spread range of friction coefficient](image)

**Fig. 4** - The influence of normal load and sliding speed on the average and the spread range of friction coefficient

![Fig. 5 - SEM images for blocks made of PBX, F = 15 N](image)

**Fig. 5** - SEM images for blocks made of PBX, F = 15 N
Because of their visco-elastic nature, the fibers almost perpendicular to the friction surface do not remain up the surface, being deformed when the matrix is torn off from the tribolayer (Fig. 6b and c), even if the test condition differ from slow speed (v = 0.25 m/s) to high one (v = 0.75 m/s) (Fig. 7). And the surface of aramid fiber is deformed, printed, but not scratched, the wear debris have few and small fiber fragments (see Fig. 8c).

Comparing these SEM images to those presented by Chang and Friedrich (Chang, 2013), due to the elasticity of fibers and to a good adherence of their adherence to the matrix, the fibers do not remain outside the surface of the matrix and the load distribution would be better. The fiber detaching from the matrix is taking place especially for fibers that are positioned along or inclined to the surface (Fig. 6a and Fig. 8d). The surface of the fibers undergoing the load seems to be less influenced by the sliding speed increase (Fig. 7), the fibers being deformed and not fragmented or scratch by the asperities of the metallic surface. Even if the load increases from 15 N to 30 N, this does not evidently change the fibers behavior. Only the matrix seems to be soften, but it has a good adherence to the fibers, even after testing at F = 30 N.

Few polymers exhibit a continuous film transfer, similar to that of PTFE (Stachowiack, 2001), (Myshkin, 2005) and high density polyethylene (HDPE) and ultra-high-molecular weight polyethylene (UHMWPE). Their similar behavior would be caused by a ‘smooth molecular profile’ or the absence of side groups in the molecular chain. Yet, polyamide was proved to have a continuous transfer film on a steel pin (Maffe, 2010), but in actual tribosystems it is difficult to investigate this aspect. The majority of polymers and polymer composites exhibit a ‘lumpy transfer’ when sliding against a hard counterface (Wieleba, 2007). PBT molecules are not too “smooth” and this could explain its tendency not to creep when a metallic surface is sliding against. The size of these lumps depends on friction pair of materials, test conditions and could vary in a large dimensional range (from microns to millimeters) (Fig. 8a).
polymer materials have better lubricating properties than others (i.e. PTFE), however, they exhibit low mechanical properties and, therefore, they are used as fillers to other more robust polymer matrix, like PEEK (Greco, 2011), (Li, 2009), (Ye, 2014).

Due to wear debris generation and fragmentation of the already transferred islands, the dry regime of a friction couple polymeric material – steel should be analyzed as a ‘third body’ tribosystem (Myshkin, 2005).

In this study, on both PBT materials, fatigues cracks were not noticed, but fatigue micro-cracks appear on transferred lumps (see Fig. 8c) and possible detaching of a wear particle will worsen the surface quality of the ring. Load and speed variation does not appear to give a strong correlation between film transfer covering area on the steel ring and its thickness, the islands of polymer adhesion on steel being similar for both polymer and composite (compare Fig. 8b and Fig. 7a), this conclusion being also pointed out by Laux and Schwartz (Laux, 2013), for different grades of PEEK. A strong correlation does not appear to exist between film thickness and volumetric wear.

Aramid fibers are not crushed and fragmented as the glass fibers and glass beads do under the load (Georgescu, 2012), (Maftei, 2010). SEM images reveal the detaching mechanisms of aramid fibers from the tribolayer and even the way they are fixed on the steel texture imply a “drag” of these worn fibers (but not fragmented) along the contact (Fig. 8d and 8f), making the friction coefficient to oscillate (see Fig. 3, for load F = 5 N and 30 N). During sliding, individual lands meet, merge and detach, forming a discontinuous transfer film. Analyzing
Fig. 8a, 8b and 8c, one may notice a high dynamics of generating, adhering and detaching, partially or entirely, of the wear debris; big debris are rare but make the friction coefficient to oscillate.

Wear maps are very useful in comparing tendencies of wear evolution for different materials sliding on the same surface (here, hardened steel). Figure 9 evidences a lower temperature for the friction couple with the block made of composite with aramid fibers, for higher speed (0.5 m/s...0.75 m/s) and higher loads (15 N... 30 N). For low values of speed and load, it seems that the neat polymer also keeps the contact temperature close to that of the composite. Other parameters will make the selection between the two materials.

The wear maps were plotted using MATLAB R2009b, the wear parameter (mass loss) being represented for each material as a function of sliding speed and normal force, with the help of a cubic interpolation.

![Temperature maps](image1)

Fig. 9 - Temperature maps (maximum values on the lateral side of the contact) at the end of the test

![Wear maps](image2)

Fig. 10 - Wear maps generated with the help of experimental data (sliding distance of 5000 m)

Mass loss of the block is lower for the composite, especially at low speed $v = 0.25$ m/s (Fig. 10). This could assume that abrasive wear under $F = 30$ N is more intense for the polymer and thus, it may be assumed that fibers avoid the polymer to be plough and tear off from the tribolayers. The composite is sensitive to low load ($F = 5$ N) and have higher values for the mass loss because the fiber are easier to be detached from the matrix when normal load is low.
CONCLUSIONS

Based on the experimental data, the authors recommend the composite for functioning in the tested ranges for speed and force, as its wear (see Fig. 10) and temperature in contact (see Fig. 9) are reduced and the friction coefficient is higher only with less 20% as compared to that exhibits by neat polymer, under the same test conditions.

The wear maps plotted based on the experimental results help to rank the tested materials and to point out several advantages of a block made of PBX:

- it allows for decreasing the temperature in contact (as measured at the lateral point of the contact) with 5...10º C for the highest values of the testing parameters (F = 20...30 N and \( v = 0.5...0.75 \) m/s); but, for low speed and load, the difference in temperature is almost insensible to the block material;

- wear is reduced almost twice for F = 15...30 N and all tested speed range;

- wear is less dependent on speed, recommending the composite for applications with variable parameter regimes;

- the friction coefficient is only several percentage higher as compared to that obtained for the block made of PBT, except the higher speed (\( v = 0.75 \) m/s).

The SEM images pointed out a very particular lumpy transfer, both for polymer and composite, meaning the leading factor is the matrix material (PBT).

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