DOI: 10.24874/ti.1621.02.24.02

Tribology in Industry

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RESEARCH

Polymeric Composites: Failures in Dry Sliding on Steel

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Keywords:

Tribology
Polymeric composite
Failure mechanisms
Wear
Friction
Electronic scanning microscopy
EDX

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Received: 12 December 2023
Revised: 22 January 2023
Accepted: 21 February 2023

A B S T R A C T

The investigation of a tribosystem failure is important in establishing its causes with the highest probability. This paper proposes a discussion on particular aspects of failure in polymeric composites sliding against steel in dry regime. At micro level, failure mechanisms of polymeric composites in dry sliding on steel could explain damages or malfunctioning at macro scale and initiate solutions. Investigating the tribolayers of both components in contact by scanning electron microscopy or optical microscopy helps identifying dominant wear mechanisms and failures produces under given operating conditions of the system. These conditions could be partially or totally reproduced at laboratory scale, with simpler testers that will facilitate this investigation at micro scale. The authors concluded that these studies of the failure mechanisms, based on images before and after test end are beneficial in understanding the tribological behavior of polymeric composite sliding against steel and in improving the operating parameters of a system, including precision, durability, maintenance and could be the initiation of formulating a new composite, a new shape or/and a new set of functioning parameters of the system.

1. INTRODUCTION

When selecting a polymer or a polymeric material (either a composite or a blend), the designer has in mind the well-known "polymer pyramid". The concept for polymer ranking like that is not new, but professor Malcolm Fox include here elastomers and new entry on the market polymers that have founding particular application in tribology [1].

We would like to add here that, now, in tribology, the polymers could be ranking in solid polymers for machine components, gels and fluid polymers, foils and fibres. Thus, polymers could play any role in a composite suited for tribological application: matrix, reinforcement, solid lubricant. And these is a very versatile approach in using polymeric materials.

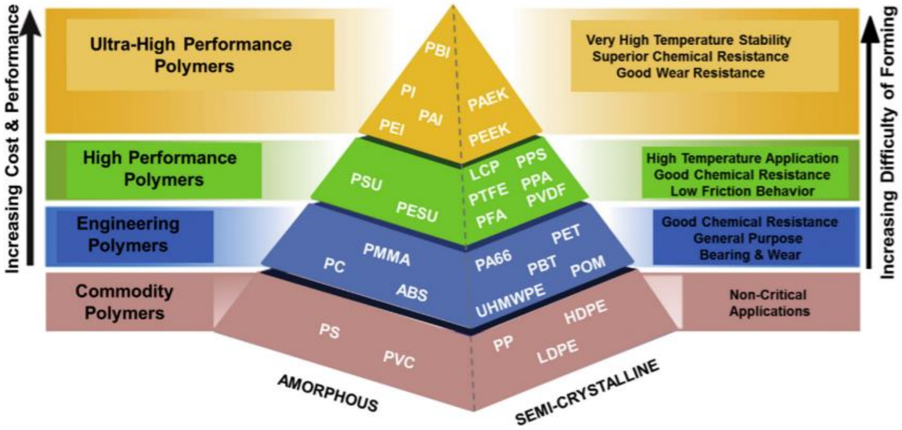

Fig. 1. Ranking of polymers taking into account their performances and their manufacturing [2].

Figure 1 presents a ranking pyramid of polymers, presented by Friedrich [2] in a recent review on polymer tribology, with four families, including tribological aspect like friction, wear, thermal resistance, but elastomers are not pointed out. There are several variants of this classification, but this includes both performance and manufacturing and one may notice that engineering polymers are especially related to wear and chemical resistance. When temperature is a restrictive demand in design, the nest class, "high performance polymers", offers several grades.

"General use" polymers or commodity polymers are included in the base of the pyramid: PS (polystyrene), PVC (polyvinyl chloride), PP (polypropylene), and pe (various grades of polyethylene) are relatively weak materials, with tensile strengths, of the order of 20 MPa. They have low relative density, with limited temperature operating ranges up to 100 °c and they are cheap, (<1…2 €/kg), materials which are produced internationally, but designers do not rely on their mechanical resistance. "Engineering polymers", such as PA (polyamides) and PET and PBT (polyesters like polyethylene terephthalate and polybutylene terephthalate) have higher strengths, typically 75 MPa with continuous operating temperatures up to 110/120 °C and a price range up to 10-15 €/kg. "High performance" polymers have been used especially in developed countries and have better thermo-physical properties, and very good resistance to degradation and cost up to 100-150€/kg. The top of this pyramid is reserved for "ultra-high performance polymers", with very high melting points, higher strength, such as the polyaramids (the well-known trade names being Kevlar/Nomex, Twaron) and the PAEK family which includes polyetheretherketone (PEEK), with strength limit up to 100 MPa, melting point around 340 °C and an operating temperature till 250 °C, produced by specialised companies, with prices upwards 100-150 €/kg.

But the engineer designer has to pay a carefully attention to polymers that combine very different properties in a set that makes them unique and very adequate to particular applications. Here, we mention PTFE that have no extraordinary mechanical resistance, but it is a very good additive in other materials, including in polymeric blends and composites, for dry and lubricated regimes.

2. INVESTIGATION OF A FRIBOLOGICAL FAILURE

The chart in Figure 2 is based on a paper writen by Ernest Rabinowicz, intitled „Investigation of a Tribological Failure" published in Wear, in 1990, that the authors have revised in order to serve better for a failure analysis.

For an actual tribosystem, the objectives of the failure analysis could be the development or the improvement of a product, reducing cost of maintenance, establishing the responsibility of the designer or/and user in order to get reparations for financial and physical damage and, not the least, prevention against re-appearance of the failure and its consequences. In laboratory research, the failure investigation of the triboelements could reveal how the components could fail and which parameters are influencing the intensity of damaging processes and how to minimize it in order to prolong the system life and its reliability. Polymeric materials could fail easier and faster because even if their properties could vary in a narrow range, the consequences could be dramatic. For steel parts an increase of the temperature with 50-100°C could be endurable for a still good functioning, but for a polymeric component even 10-15°C variation could produce the failure or a drastic modification of the functioning parameters.

Investigation of a tribosystem failure

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Study of the history of the system
- the evolution in time of loads, speeds, temperature, environment characteristics
- materials (solid bodies, lubricant(s))
- external influences from in-line systems related to the analyzed one
- make a scenario of the failure
- document on similar cases (if any)

↓

Inspection the components of the systems
- measuring system (if any)
- wear traces, with photos at macro and micro scales
- collect wear debris, samples of lubricant(s), parameters recordings (load, velocity, temperature, acoustic emission etc.)
- imagine possible tests to point out the changes in the materials, parameters evolution (temperature, friction, noise etc.)
- investigations (including SEM, DSC, FTIR, EDX)

↓

Analysis of results of the previous steps
- establish dominant wear/failure mechanisms
- investigate surface quality after failure and compare to initial one or to those after normal functioning
- analyze the temperature evolution especially in or near contacts, of the lubricant
- analysis of lubricant and its supply in contact
- analyze the evolution of environment parameters
- identify wear mechanisms
- search for suppressed effects etc.)
- develop simulations and/or models based on already collected data
- establish supplementary laboratory tests and investigations (SEM, EDX, FTIR

↓

Conclusions
- establish the causes with the highest probability
- imagine/design solutions for avoiding/delay/reduce the failure/damage or even for improving the system functioning
- eliminate, reduce the cause(s) of the failure
- change the design and the functioning parameters of the system (re-engineering) but take into account cost and time.

Fig. 2. Investigation of a tribosystem failure (flowchart after [3]).

A single result, especially from a test, not from an actual system, is not enough to describe the failure and to explain its development and causes. Thus, before testing it is necessary to have a plan of testing (a campaign) including the influencing factors that are desired to be studied and their range of variation.

What errors could do a research team? There are enumerated several, but it could be more:

- not selecting the adequate tribotester,
- not selecting relevant factors influencing the friction couple,
- jumping to conclusions before finishing the test campaign and to verify the repeatability of the test results,
- not understanding how the failure develops,
- not imagine all possible failure causes,
- not recording all the parameters that the test equipment, the monitoring and measuring apparatus could survey,
- not asking colleagues with different specializations that could have another opinion,
- considering the test too simple,
- destroying evidence due to lack of planning, sample storing and manipulation.

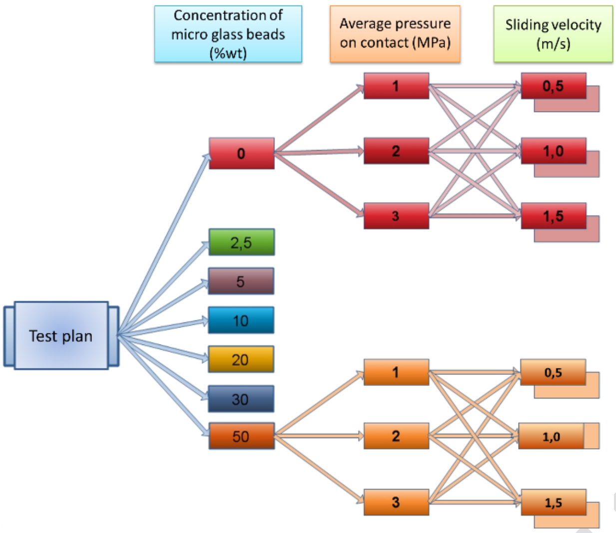
Figure 3 presents two test plans, each one with different objective:

a) a test plan to establish the influence of reinforcement concentrations (micro glass beads) in a PA6 matrix, on tribological behaviour, described by three characteristics, friction coefficient, wear of the disk and wear of the pin, and the temperature developed near contact, monitored with a thermo-vision camera; as the study involved six values for the glass bead concentration (2.5%, 5%, 10%, 20%, 30% and 50%, wt.), the experimental results could point out that 20% was an optimum for reducing wear, especially.

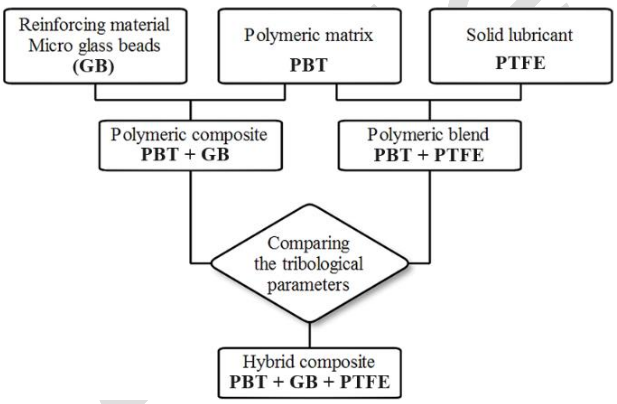
b) a test plan for developing a new hybrid composite, based on PBT matrix and glass beads as reinforcement and PTFE as solid lubricant: there were tested under the same conditions (load and velocity) blocks made of PBT, composites with micro glass beads (concentrations of 10%, 20% and 30%, wt.), blends PBT + PTFE (PTFE concentrations of

5%, 10% and 20%, wt.); their tribological parameters were compared and it was formulated a hybrid composite, PBT +10 % glass beads and 10% PTFE, that proved to have a set of advantageous tribological behaviour.

Progress in electron microscopy technique has allowed to exceed the magnification limits and resolution of the optical microscopy.



(a) Test plan for evaluating the influence of reinforcement concentration on tribological behaviour [4].



(b) Test plan for developing a new hybrid composite [5].

Fig. 3. Examples of test plans.

SEM is the most widely imaging and non-destructive technique, through the sample surface is scanned by the electrons at a higher acceleration voltage [6]. Due to the non-conductive character of thermoplastic polymers, they could not resist to the electron beam impact with higher energy generating artefacts. Further, the „lighter" elements from the polymer composition induced poor contrast of the image. So, prior to morphology characterization, the surface need to be sputter-coated (few namometers of metallic layer, gold, silver, preferably) to gain complete information about the microstructure or failure mechanism understanding.

3. FAILURE MECHANISMS IN TRIBOSYSTEMS WITH POLYMERS AND POLYMER BLENDS AND COMPOSITES

The main solutions for reducing friction in a tribosystem with at least one component made of polymer or polymer composite:

- inclusion of solid (soft) fillers,
- external lubrication,
- intrinsic (internal) lubrication
- another issue related to the use of polymeric materials in tribology is reducing wear and this could be achieved by
- adding reinforcement (it could induce an increase of friction coefficient), with different shape and nature: powders, short fibres (glass, carbon, even polymeric like aramid), wool,
- adding solid or grease lubricants; several polymers like PTFE could be a very efficient solid lubricant in harder polymers (the result being a polymeric blend) or even in composites,
- harder polymeric matrix, but more expensive (for instance peek).

Figure 4 presents all damages described that could be noticed in the polymeric materials, but they are differentiated for each of the three classes of polymeric materials: neat polymers, composites and polymeric blends. Also, the mixtures could be based on thermosets, thermoplastics or/and elastomers). It is obvious that damages could overlap, for instance, fatigue and wear, or tribocorrosion and abrasive wear etc. For instance, for the same polymer used as main and only material for a component, the abrasive wear could be more intense as compared to the same polymer blended with a higher strength polymer or in a composite that contains harder fillers (like whiskers of glass, short carbon fibres, glass beads etc.).

The counterparts made of steel could have also abrasive wear more intense, but reasonable to ensure the tribosystem is operating in the designed range. One of the conclusions of this discussion is that a failure of a tribosystem should be analysed taking into account damages on all bodies involved in motion under load and the investigator has to have in mind that what he saw is the results of that tribosystem with its characteristics (the solid bodies, lubricant, regime and environment) and that changing even one of these would affect the entire system.

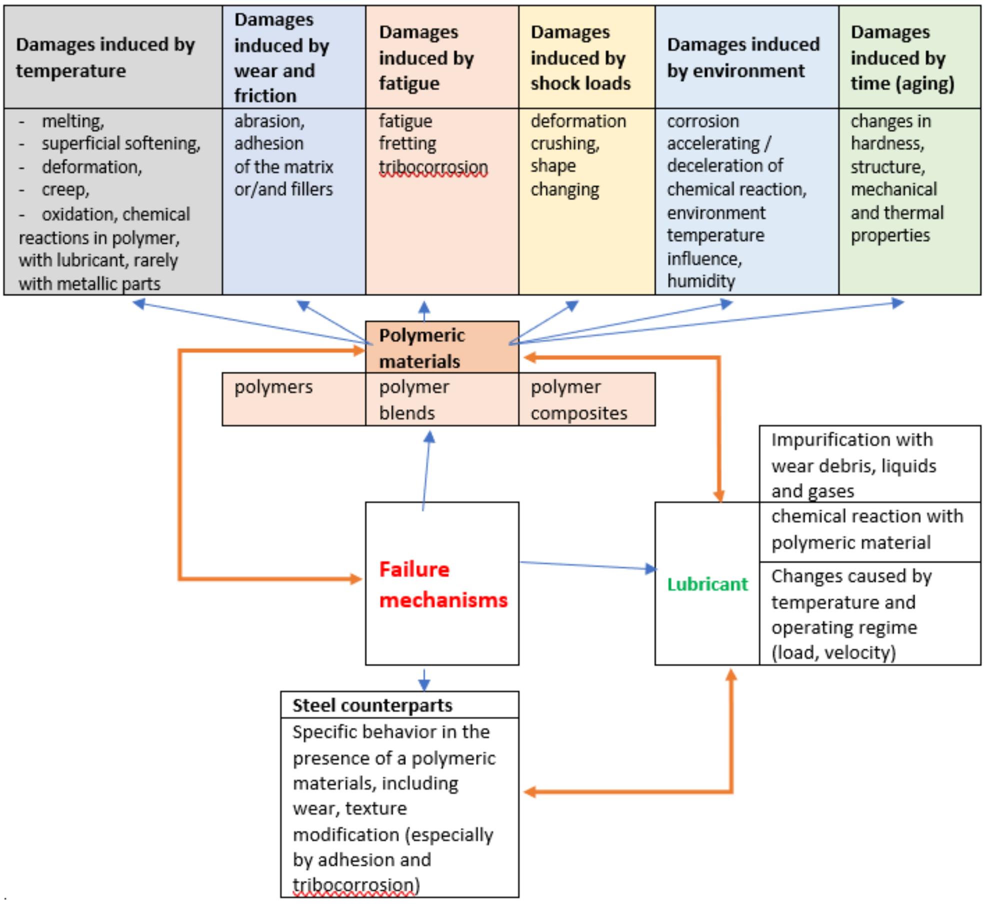


Fig. 4. Investigation of a tribosystem failure with triboelement(s) made of polymeric materials.

Figure 5 presents a typical surface damage of a disk made of PA6 after being worn with a steel pin and all three mention wear mechanisms (abrasion, adhesion and fatigue is noticed on the SEM image). The polymers have specific features of these wear mechanisms. There are identify two types of wear, mild and severe. And for each, polymers have specific features of these wear mechanisms.

For instance, in contact with steel counter-parts, polymer abrasion intensity could be reduced due to the adhesion of the polymer on the hard surfaces. Chronologically, the polymer is pulled off by the hard asperities (that is an abrasive process) and then, the wear debris is pressed against the counterpart surface, where it is mechanically (rarely chemically, too) fixed in the texture surface, levelling the surface with hard asperities. Even this transfer does not cover all the hard texture, the asperities are smaller and less numerous. They cannot anymore detached microvolumes of polymers, they only deform the polymer surface with micro-channels in the sliding direction.

The conclusion of this scenario characteristic for the polymeric material sliding against a harder surface is that wear mechanisms act simultaneously, and locally, one wear type could be identified, but at macro scale, the result is synergic, being dominant one of these mechanisms. Also, the wear character is changing in time. Initially, the movement produces abrasion, then, the wear debris are transfer and later fatigue initiates micro-cracks, almost perpendicular to sliding direction. Figure 5 presents wear mechanisms identified on a disk made of PA6, sliding against a hard steel pin, at the end of the test.

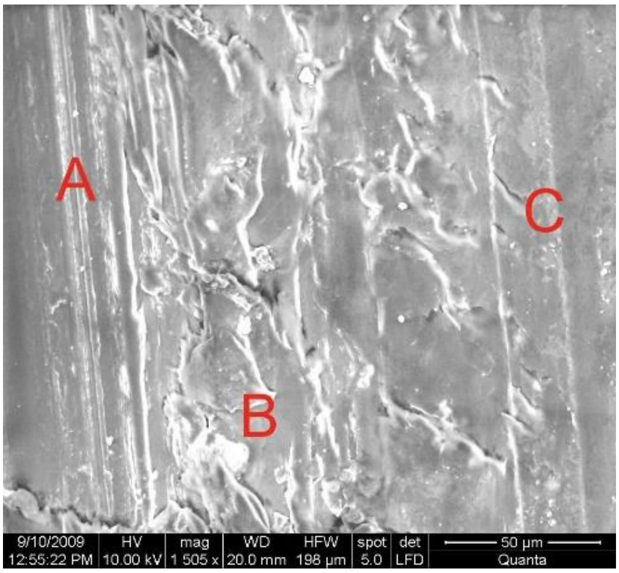
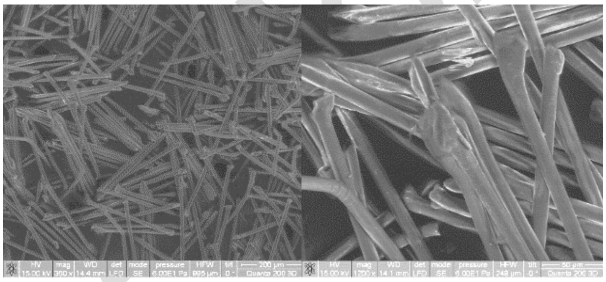
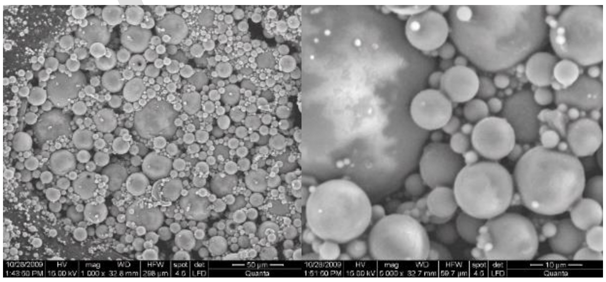


Fig. 5. Wear mechanisms identified on the wear track on a disk made of PA6: A – abrasive wear, B – adhesion wear (re-adhesion of wear debris already detached), C – fatigue cracks, Test conditions: average pressure on pin 3 MPa, sliding velocity 1.5 m/s and sliding distance 5 km [4]

An "advantage" of wear debris made of polymer is that, being easily deformed, they could be rolled, acting like micro-rollers till local force deformed them and they could be either fixed in the harder texture or embedded in the softer material (the polymer) without producing damages as a hard particle. When wear particles become too great or the transfer film too non-uniform, they disturb motion, increase the friction coefficient and, under load they detach bigger volume of material especially from the softer (less resistant) one.



Aramid fibers [9]



Micro glass beads [5,4]

Fig. 6. Adding materials reinforcement glass beads.

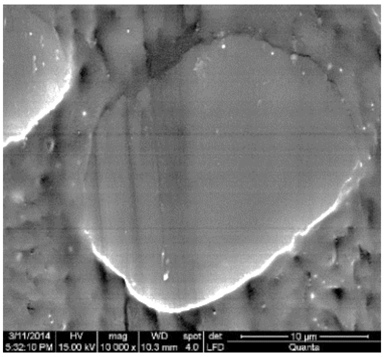
The presence of reinforcement, as short fibres, micro-plates or particles with similar dimensions (almost spherical) fixed the polymer and does not allow for being torn off in larger micro-volumes. Of course, nature, shape and concentration of the reinforcement make the designer to accept a compromise for the set of tribological characteristics.

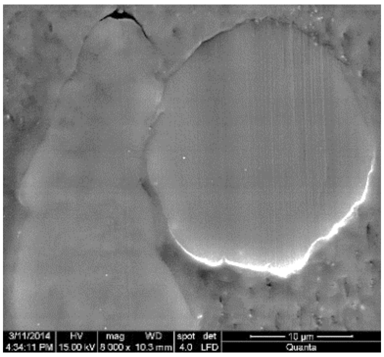
The examples given in this paper are taken from research works based on two types of reinforcement (Figure 6): micro glass beads with diameters in the range 2-20 microns and short aramid fibres (of 250 μm in length, code Twaron D1088).

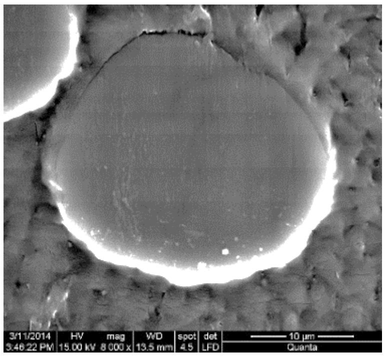
These fibres or whiskers, due to cutting process, have their ends as a nail head, that help them to fix the polymer matrix and to be more difficult to be extract from the softer material.

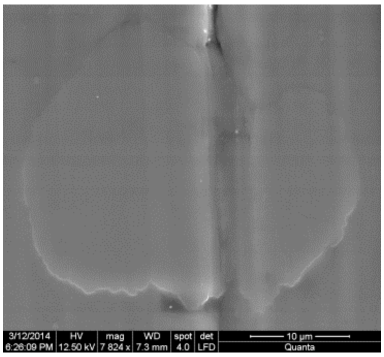
Figure 7 points out the influence of the combination matrix + fibre reinforcement. There are presented short aramid fibres [9] in PA6 matrix (a, b and c) and in PBT matrix (c, d and e), both having similar mechanical characteristics (PBT has 90-95 Shore D as compared to 80-95 for PA6) and having a closer melting point (around 223°C), but the tribological behaviour is different, especially in the presence of a filler. There are presented typical aspects of a short aramid fibre in PA6 matrix (a, b and c) and in PBT matrix (e, f and g), obtained on block-on-ring (harden steel) tester, contact length 4 mm, normal load 30 N.

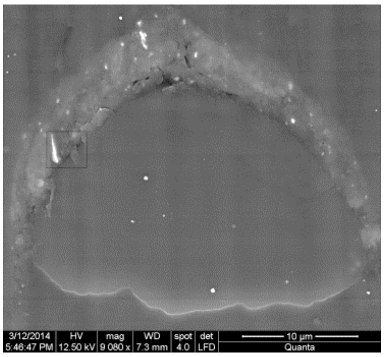
When the sliding velocity increases, the heat generation increases and the matrix is softened, even on a small thickness of the superficial layer. PA6 was easier detached than PBT the fibres were left uncovered and they were obliged to sustain the load. the sliding caused small detachment of the fibre from the matrix behind the contact and smaller wear debris are trapped in this space. one may also notice micro-volumes of polymer melt and laminated, partially rolled. at low velocity, the fibre could have marks of abrasion (d) as it could not be embedded in the polymer matrix as, under this regime, it is not softened (v=0.25 m/s). At higher speed, fibre could be embedded as the polymer has a higher temperature and, thus, lower mechanical resistance.


(a) v=0.25 m/s


(b) v=0.5 m/s


(c) v=0.75 m/s


(d) v=0.25 m/s


(e) v=0.5 m/s

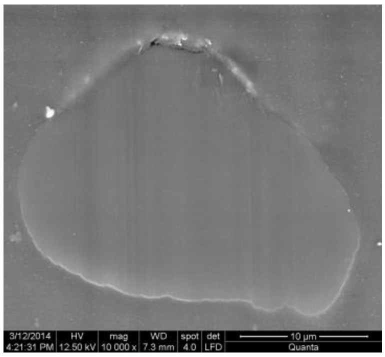
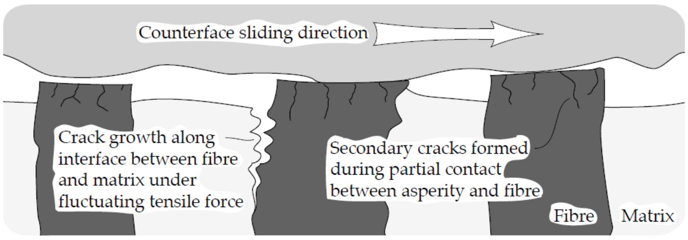
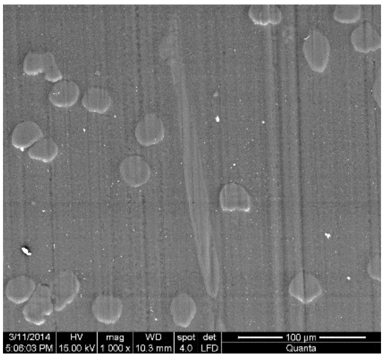
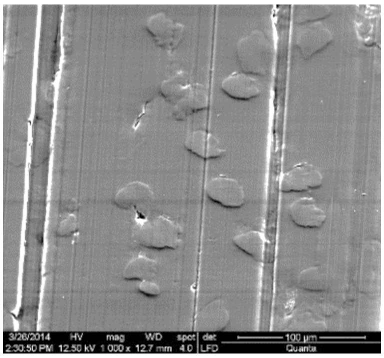

(f) v=0.75 m/s

Fig. 7. Aramid fiber in matrix made of PA6 (a, b and c) and in PBT matrix (d, e and f), F= 30 N, L=5 km, block-on-ring [9].



(a) A model of the fibre behaviour in a polymer matrix [10].


(b) F=30 N, v=0.25 m/s, PAX [9]


(c) F=15 N, v=0.25 PBX [9]

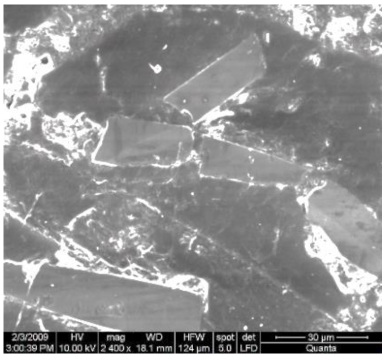

(d) PTFE + 40%wt glass fibres [12]

Fig. 8. Typical worn traces of composites sliding against steel: a) and b) dry sliding, L=5 km, block-on-ring, c) composite sliding against steel in water, shoe-on-shaft, L=10 km.

A relevant model of the behaviour of a fibre in soft matrix is presented in [10] (Figure 8a) and also described in [11]. The asperities of the counter surface preferentially dislodge the polymer and the fibres remain to support by themselves the load. Due to sliding and their elasticity, the fibres are debonded from the matrix.

If the fibres are more rigid as carbon fibre and glass fibre, it will eventually fracture and the fragments will be dragged along the contact, producing abrasive wear, or they will be embedded in the polymeric matrix, enriching the superficial layer in hard particle, fixing the matrix against tearing-off process.

A too high concentration of hard particles in the superficial layer will increase the wear of the counter face and the friction coefficient. The elastic fibres as the aramid ones could be bend or even dislocated if they are near surface. Figure 8b and c presents the aspect of two composites with short aramid fibres, confirming the model and Figure 8d presents fractures of the hard fillers (glass fibres), caused by their agglomeration. This agglomeration was the result of losing the soft matrix due to preferential abrasive wear.

Adhesion of polymers and their mixtures (blends or composites) have typical aspect and depends on the polymer nature. Adhesion could be the result of only a mechanical process of transfer or could imply also chemical reactions if temperature in contact is favourable to develop them. Transfer and adhesion are more intense in dry sliding and less in lubricated contact.

The values of two tribological characteristics reveal that the new created hybrid composite has the advantage of reducing wear and make it less sensitive to sliding velocity, but the disadvantage of increasing the friction coefficient (Figure 9).

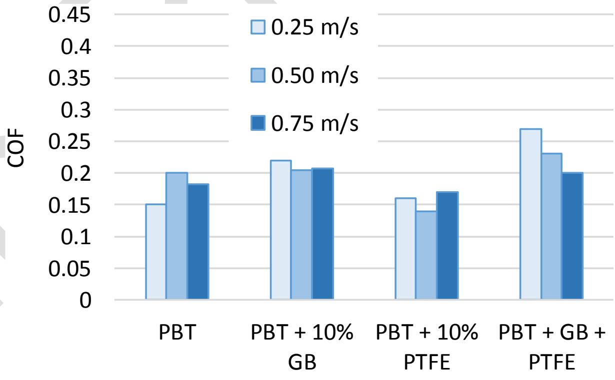
There are polymers that have transfer (adhesion) processes that are favorable to improve tribological characteristics, as PTFE, UHMWPE, that could form continuous films, reducing wear and friction, but there are other polymers for which the transfer is generated in lumpy volumes, with a decrease in tribological performances of the system. Figure 10 presents typical adhesion on the steel surface for

a) the transfer film made of PTFE is almost continuous,

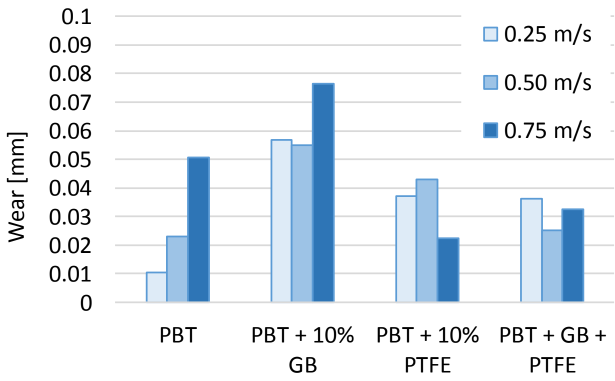
b) lumpy transfer when the block is made of PBT + 10 % glass beads + 10% PTFE; the transferred material contains a blend of PBT and PTFE, maybe very small fragments of glass (but block surface revealed that no broken glass beads were found, at least in the investigated surface; adding PTFE in the composite makes it softer and when load in concentrated on beads, these ones are pressed into the softer polymer blend of PBT and PTFE,

c) transfer on steel ring from a block made of PBT +10% glass beads; there is a relatively bigger bead trapped in the steel texture that was cracked under load; this could accelerate the wear of the block; smaller beads are pushed into the valleys of the surfaces together with the polymer.

The wear mechanisms have a qualitative interpretation as at micro-scale there are many wear damaging mechanisms, but at the system scale, the interpretation has to be done by quantities of tribological characteristics [13,14,15]. Putting together these qualitative and quantitative analyses, the tribologist could give explanations of failures, recommendations for avoiding or reducing them, selecting the polymeric material that suits better for the applications in contact with steel.



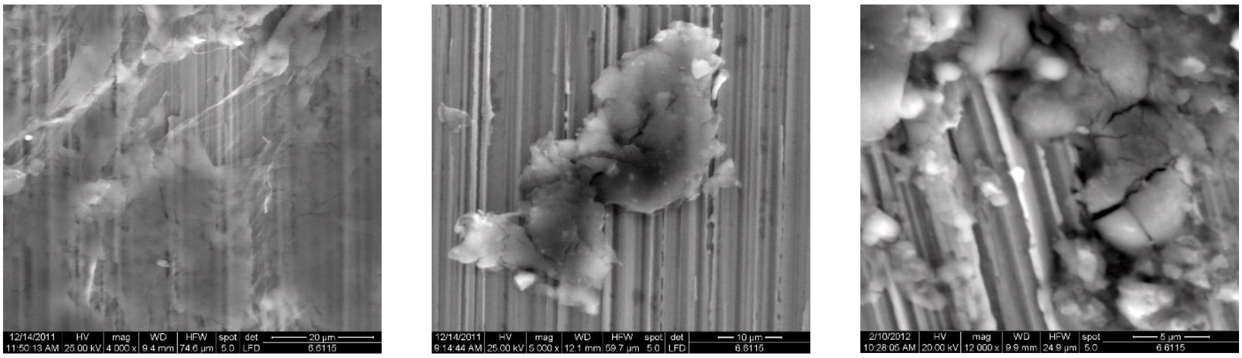
(a)



(b)

Fig. 9. F= 5 N, L=7.5 km.

The decrease of friction coefficient for the hybrid composite when the velocity increases could be explained: heat generation in contact depends on the quantity of mechanical work, the matrix rises its temperature, becomes softer and the glass beads could be embedded in it, also the PTFE will be more effective as a solid lubricant as it could be easier spread on the surfaces in contact.

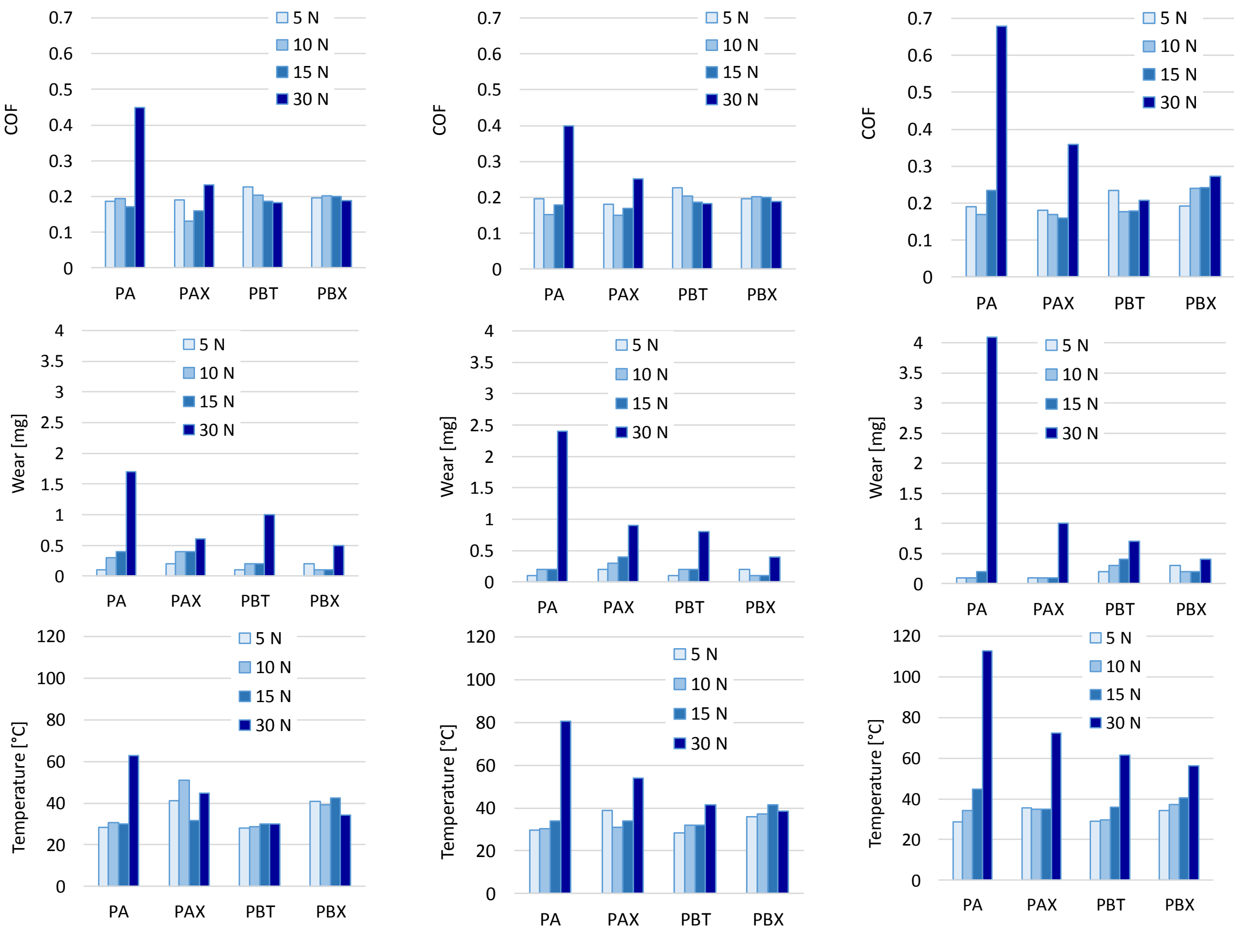


(a) Steel ring with transfer film (almost continuous), block made of PTFE, v=0.75 m/s

(b) Lumpy adhesion on steel ring, block made of PBT + 10% glass beads +10% PTFE, v=0.75 m/s

(c) Transfer on steel ring when using a block made of PBT + 10% glass beads, v=0.5 m/

Fig. 10. Adhesion processes for materials with PBT matrix, in dry sliding against rolling bearing steel [5], F=5 N, L=7.5 km.



(a) v=0.25 m/s

(b) v=0.5 m/s

(c) v=0.75 m/s

Fig. 11. Wear of the block from a block-on-ring test, ring made of rolling bearing steel (data organized after test results from [9]: PAX – composite PA6 +10 % short aramid fibers, PBX – composite PBT + 10% short aramid fibres.

Figure 11 presents at the same scale, three tribological characteristics, for four materials sliding against steel, under the same conditions, it is possible to select the one that offers the more adequate set of values for the tested materials. This figure points out that the tribological behavior has to be assessed by experimental tests and not based on other thermal and mechanical characteristics of the material of interest. Both polymers (PA6 and PBT has good results for low load (F=5 N), but when load increases, PBT has higher values for F=10 N and 15 N than those of PA6 only for v=0.75 m/s, these could be explained that PA6 as matrix becomes softer and it is not removed as solid wear debris and also because this polymer re-adheres the wear its polymeric debris. But for highest load (F=30 N) PBT has the lowest mass loss. Both composites, PAX and PBX has a better wear resistance as compared to the base-polymer, except PAX in the range of F=5-15 N for v=0.25-0.5 m/s). Taking into account the highest load (F=30 N), the material with reduced wear was PBX, recommending it for more loaded linear contact. For lower loads, both polymers are suited instead of a more expensive composite. At v=0.75 m/s, the composite with PBT matrix is less sensitive to load, this being a recommendation for variable regime in load.

4. CONCLUSIONS

The failure mechanisms in sliding contact polymer–steel or polymeric composite–steel are discussed based on tests done by the authors or found in open literature.

All failures start at micro levels and extend their influence till the system could not support any more modifications and breaks. Knowing the composite characteristics, making visible the failures having nano and micro dimensions, the researchers could propose other variants of the composite, modifications in shapes and exploitation regime to maintain the system at a required reliability.

Based on experimental data presented in this paper, the investigation of failure mechanisms in tribological systems involving at least one component made of polymeric material is important in order to understand the wear mechanisms, and based on the interpretation, the researcher could propose solutions for improving the tribology of this contact: selecting other polymeric materials with verified better performances under the same conditions, changes shapes and, if possible, modifying the exploitation regime in order to reduce wear, friction and temperature in contact.

The user could eliminate or reduce these causes and the design engineer could imagine solutions for avoiding, delay or/and reduce the failure damages. Thus, the designer will have information to change shapes, materials, operating parameters and their interactions, taking into account factors and time and cost. This is a re-engineering loop that makes progress.

Acknowledgement

The authors want to express their gratitude to SC MONOFIL SRL Savinesti, Romania, especially to researcher eng. Doina Constantinescu, PhD, for manufacturing the polymeric samples tested by the authors.

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