Chapter

Tribological Behavior of Polymers and Polymer Composites

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Abstract

This chapter means to explain the tribological behavior of polymer-based materials, to support a beneficial introducing of those materials in actual applications based on test campaigns and their results. Generally, the designers have to take into consideration a set of tribological parameters, not only one, including friction coefficient, wear, temperature in contact, contact durability related to application. Adding materials in polymers could improve especially wear with more than one order of magnitude, but when harder fillers are added (as glass beads, short fibers, minerals) the friction coefficient is slightly increased as compared to neat polymer. In this chapter, there are presented several research studies done by the authors, from which there is point out the importance of composite formulation based on experimental results. For instance, for PBT sliding on steel there was obtained a friction coefficient between 0.15 and 0.3, but for the composite with PBT + micro glass beads, the value of friction coefficient was greater. Adding a polymer playing the role of a solid lubricant (PTFE) in these composites and also only in PBT, decreased the friction coefficient till a maximum value of 0.25. The wear parameter, linear wear rate of the block (from block-on-ring tester) was reduced from 4.5 μm/(N·km) till bellow 1 μm/(N·km) for a dry sliding regime of 2.5 … 5 N, for all tested sliding velocities, for the composite PBT + 10% glass beads +10% PTFE, the most promising composite from this family of materials. This study emphasis the importance of polymer composite recipe and the test parameters. Also there are presented failure mechanisms within the tribolayer of polymer-based materials and their counterparts.

Keywords: polymer, composites with polymer matrix, polymer blends, tribology, wear, friction, tribolayer, tribological behavior, wear mechanisms

1. Issues related to the use of polymeric materials in tribological applications

Plastics and materials based on plastic have become an acceptable replacement of metallic materials and, as a consequence, they have to face the challenge of having also a good tribological behavior, implying a set of characteristics favorable to a reliable functioning of the application.

Issues that an engineers (both designers and users) have to pay attention when using polymeric materials in tribological applications include dimensional stability. These materials have higher thermal expansion coefficients, shorter durability, sensitivity and particular behavior to high and low temperatures. As they are

characterized by lower hardness, they are not prone to be introduced in rolling contacts, will few exceptions (here including car tires and gears), most applications being for sliding motion (belt, sliding bearing, seals, brakes etc.).

The advantages of using polymeric materials (polymers, blends and composites) [1–5] include self-lubricity, lower density as compared to metallic materials, resistance to tribocorrosion [6] or general oxidation, non-toxic nature and potential processing to final shape, usually, by injection molding. But their favorable properties come in a package with disadvantages. One is that a slight change in working conditions (load, velocity, temperature etc.) could substantially modify tribological characteristics [7], especially wear rate and low friction is not related to low wear rate. Also, negative temperatures have different influences on polymeric materials (some become brittle, some resist without problems and some are conditioned by the working conditions and environment).

Figure 1 presents materials based on polymers and elastomers that could be used in tribological applications.

When using polymeric materials, the designer should pay attention how the component will obey design requirements, if it has dimensional stability, mechanical characteristics with reliable values, if issues related to aging are acceptable for

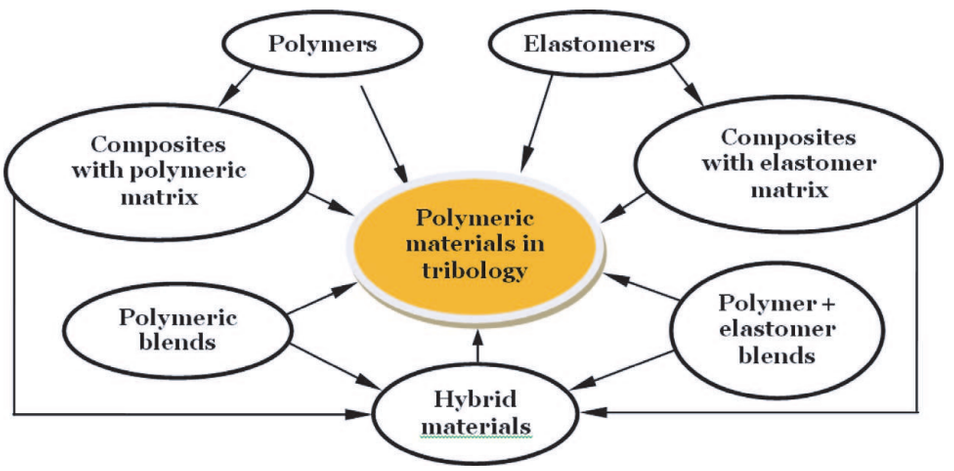


Figure 1.
Materials based on polymers and elastomers, involved in tribological applications [1–5].

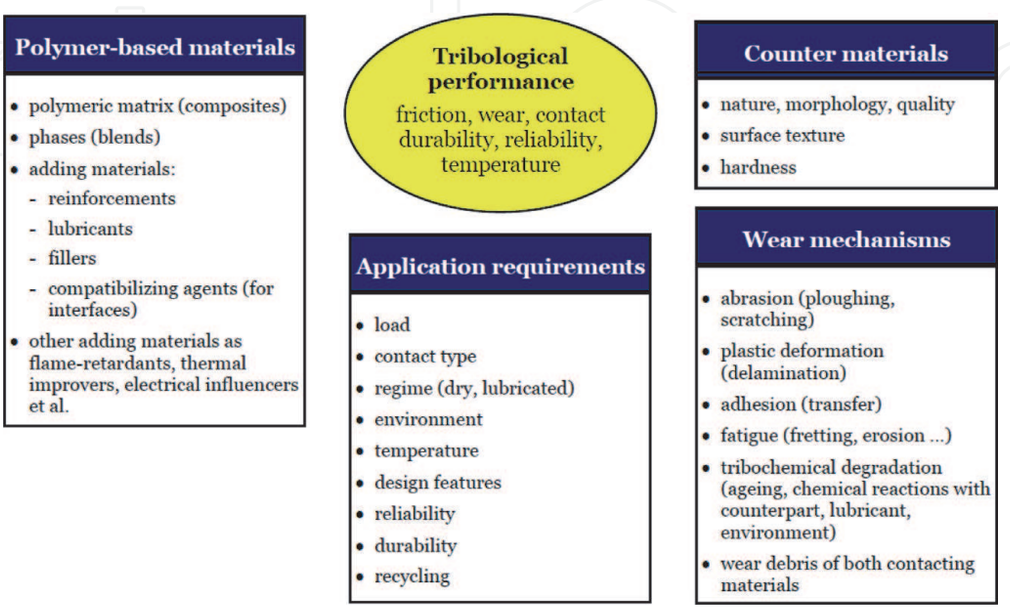


Figure 2.
A chart of significant aspects related to tribological performance implying polymeric materials.

the component durability (life time). The design should be done so that the working conditions will vary in narrow ranges (temperatures, load, velocity, material composition and morphology) [8].

The majority of tribological applications with polymeric materials are involving couples with one element made of metallic materials, the other being polymeric. Sometimes, the polymeric material is moving against a body made of the same materials, an example being gear transmissions.

Figure 2 summarizes the main aspects of tribological performance when using polymer-based materials.

2. Polymers, and materials with polymers for tribological applications

Table 1 presents the polymers used in tribological applications, several features and usual components made of them.

Polymer	Tribological characteristics
PTFE	Low friction, but high wear rate. Used both neat, as matrix and as solid lubricant. More recently, added in polymers, resulting polymer blends; in composite as solid lubricant or matrix in composite with reinforcements as glass fibers, carbon fibers, metallic powder as copper. High working temperature [9, 10]
PA	Moderate friction coefficient, low wear rate, but too sensitive to water and humidity. Working temperature quite low [11].
POM	Similar performance as PA. Good durability in rolling contacts.
PEEK	Polyetheretherketone, semicrystalline High working temperature and very good chemical resistance. Accept higher contact pressure but high friction coefficient as neat polymer [12–14]
UHMWPE	Very good wear resistance, especially against abrasion, even in water. Moderate friction coefficient. Modest working temperature.
PU	Good wear resistance in rolling contacts. Relatively high friction coefficient in sliding.
PI	High performance polymer with very good behavior in high contact pressure. Higher friction coefficient.
PBT	A reliable behavior in sliding contact, lower wear as PA, but more restrictive condition in molding. Usually with a solid lubricant or reinforcement [15, 16]
PEI	Amorphous thermal stability, very good mechanical and physical properties, easy processability, applicability and possibility of recycling and repair, thermosetting polyimides, blended with PEEK [13]
PES	Amorphous [17]
PPS	Semicrystalline, polyphenylenesulphide, water lubrication high glass transition and high melting temperature and high mechanical strength, high COF on steel in dry regime (0.4…0.5), PPS + SWCNT (0.5 wt.%) + WS_2 (1.5 wt.%) [18, 19]
PPP	Polyparaphenylene, semicrystalline, very high mechanical stability at room temperature, poor wear resistance [12]
PBI	Polybenzimidazole semicrystalline, high heat resistance and mechanical property retention, even under high temperatures [12]
Epoxy and phenolic polymers	Used especially as binder agents in composites, they induce high friction, but constant. Their brittleness induces wear by micro-detaching harder particles (as a dust) that could damage the smooth functioning of the tribosystem. The composites with these resins usually are designed for frictional applications (high and constant friction coefficient, with controlled wear evolution in time)

Table 1.
Tribological characteristics of thermoplastic polymers [5–8, 20].

Semi-crystalline polymers can be used even above their glass transition temperature (Tg), another added advantage against chemical constancy.

Various inorganic nanofillers, e.g., from metals (Cu, Fe), metallic and non-metallic oxides (CuO, ZnO, TiO_2, ZrO_2, SiO_2) and salts as silicon nitride (Si_3N_4), have been proved to not only enhancing mechanical properties, but also to lowering the friction coefficient and the rate of wear under various sliding circumstances. In particular, PEEK, PPS, and PTFE are the most widely studied polymers for different tribological applications and they are often blended with TiO_2, SiC, Si_3N_4, and carbon fiber fillers [19]. Nevertheless, it is also noted that there are no single or combined polymers or fillers that provide the best tribological performance in all conditions. Being a result of "system responses", friction and wear always depend on both the intrinsic material properties and the external environmental conditions. The beneficial effect of adding a certain material in a polymeric matrix is exemplified by tests did by Kurdi et al. [21] (**Figure 3**), 5–15% of TiO_2 reducing friction and wear at room temperature, but not at elevated temperature. Thus, functioning conditions are tremendously important when selecting a pair of materials for a good or at least acceptable tribological behavior.

Hanchi et al. [13] reported results on friction and wear under dry sliding of injection molded blends of PEEK and PEI, at temperatures from 20–232°C, on a pin-on-disk tribotester. It was found that tan δ peaks corresponding to α transitions occurring in the vicinity of the glass transition temperature (Tg) coincided with catastrophic tribological failure in the case of PEI and the amorphous PEEK/PEI blends. PEEK and the annealed 70% PEEK/30% PEI blend exhibited marked increases in friction and wear above the Tg. The absence of catastrophic tribological failure in PEEK and the annealed 70/30 blend in the vicinity of Tg corresponded to a transition of significantly lower strength those observed in PEI and the amorphous blends. Between 90°C and 105°C for PEI and 45°C and 70°C for the PEEK/PEI 50/50 blend, severe to mild friction and wear transitions were observed. It appeared that a substantial change in ductility associated with these β transitions resulted in the transitional tribological behavior.

Unal et al. reported the influence of test speed and load values on the friction and wear behavior of PTFE, POM and PEI, on a pin-on-disc tribotester. Tests were carried out at room temperature, under 5 N, 10 N and 15N and at 0,5 m/s, 0,75 m/s and 1m/s. The specific wear rates were deduced from mass loss. The results showed that, for all tested polymers, the coefficient of friction increases linearly with the increase in load. For the load and speed range of this investigation, the wear rate showed very low sensitivity to the applied load and large sensitivity to speed, particularly at high load values [22].

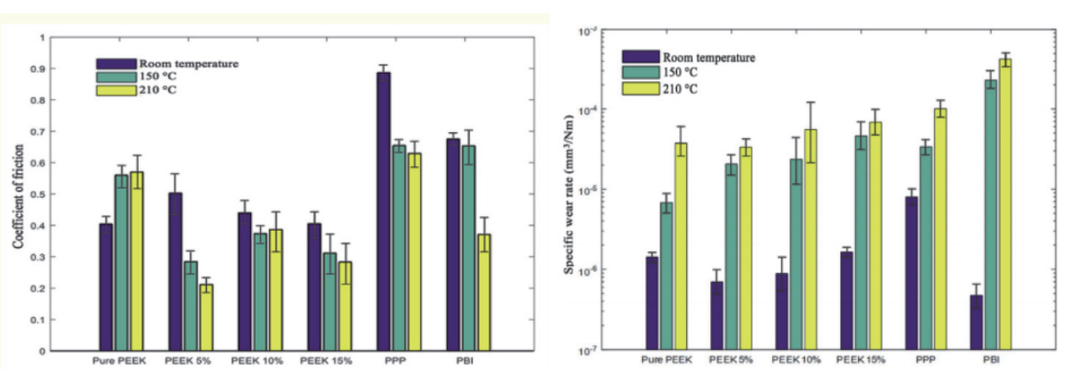


Figure 3.
Influence of percentage of TiO_2 on (a) friction coefficient and (b) specific wear rate, for a pin-on-disk configuration, in sliding at v = 0.1 m/s, average pressure p = 1 MPa, for 2 hours [21].

What do the engineers want from polymeric materials when introducing in tribological applications? A set of characteristics including thermal, mechanical and tribological ones:

- higher softening temperatures, sometimes obtained by adding short glass fibers;
- higher toughness; reinforcement could rise the flexural modulus till 11,000 MPa, a value that is overpass only by PPS in the thermoplastic polymers;
- low or acceptable friction and high wear resistance;
- good strength al negative temperature, including impact resistance;
- no or very less liquid absorption (including water)
- chemical resistance at fluids circulated in application (as lubricant or/and environment);
- good dimensional stability; low thermal expansion;
- good ability for compounding (mixing), when adding materials for reinforcement, solid lubricants, anti-ignition agents etc.,
- good processing capability (uniform flow, fast solidification and acceptably low cost and improvement by treatment).

Based on important works on tribology of polymer-based materials [3, 20, 23–25]. **Figure 4** presents a classification of adding materials taking into account the function of these materials in polymers. Generally, reinforcements [24–27] and solid lubricants in polymer-based materials improve their tribological behavior, but it is not a rule and the new recipes should be tested at laboratory scale and then the designed components at actual scale and under functioning conditions. Some solid lubricants, especially with sheet-like aspects (graphite, graphite, sulphides etc.) weaken the bulk materials as they reduce the superficial energy, but the mechanical properties are diminishing. Reinforcements in polymers make their resistance greater, but generate a more intense abrasive wear on the counterpart surface and

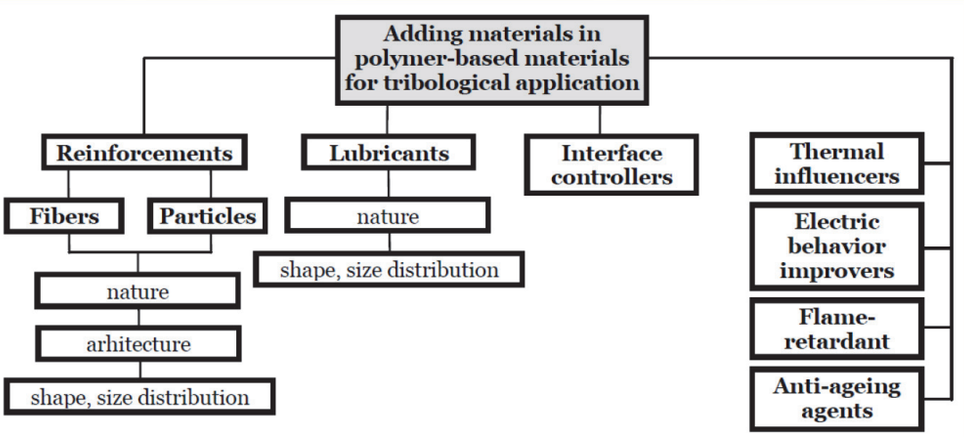


Figure 4.
A classification of materials in polymeric-based materials.

the friction coefficient is higher and the surface quality of both rubbing surfaces becomes worse. Reinforcements reduce or even damage the protective transfer films [28]. They could generate a sliding regime characterized by severe and third body wear [29]. For instance, the composite PA + 50% glass beads [11] exhibit a third body friction and wear, especially at low velocity (see **Figures 35b** and **c**).

Figure 4 points out that adding materials in polymers have different roles (sometimes, they could act in two or more directions) and the influence of the set added in the basic polymer could be synergic [30], difficult to enclose in formula, thus, testing is a necessity. **Figure 5** presents several reinforcements: a) micros glass beads with large dispersion of the bead radius (this is a favorable aspect because this large distribution allow for the small beads to fix the matrix next the bigger ones and wear is considerably reduced), b) short glass fibers with diameters of 8 ... 20 μm and length of hundred microns [31] (similarly, carbon fibers are added in 10 ... 20% wt), c) aramid fibers [16, 32] (more flexible and with nail-shape ends that help them to fix the polymer matrix).

Harder polymers and polymer composites with hard components are helped to reduce friction by adding solid lubricants with plaquette-like shape (graphite [33], graphene, disulphides [33], several examples being given in **Figure 6**) or polymers as PTFE, with more uniform transfer and having very low friction coefficient.

Tribologists considers that short fibers are more beneficial for tribological application, but recently, the polymers with long fibers were also introduced as materials for moving parts due to the advances in fibers and polymer technology. There is a short discussion about fiber architecture. Usually, short and tangle fibers are randomly organized in the material, they rarely could be oriented, but the cost will increase. Long fibers could be organized in woven, unidirectional, multi-axial,

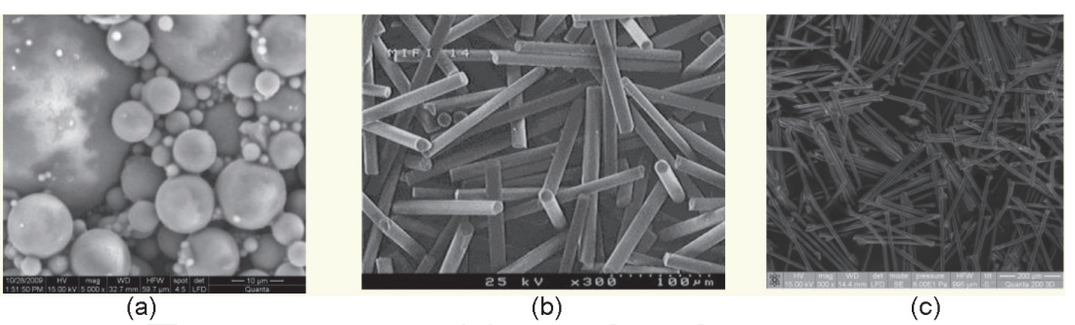


Figure 5.
Aspect of reinforcements in polymers. (a) Glass beads used in [11, 15]. (b) Short glass fibers from LANXESS [31]. (c) Short aramid fibers Twaron [16].

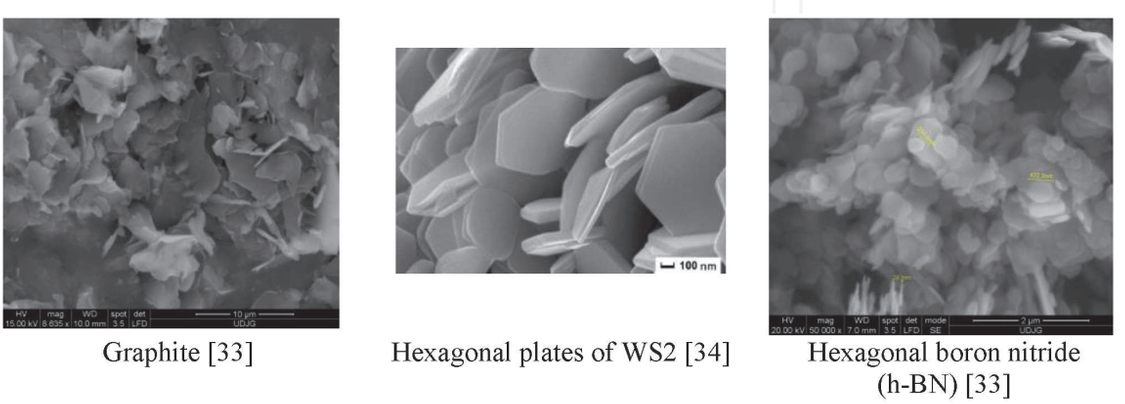


Figure 6.
Aspect of several solid lubricants introduced in polymers. Graphite [33]. Hexagonal plates of WS2 [34]. Hexagonal boron nitride (h-BN) [33].

depending on the other requirements besides the tribological one. Being organized, the wear of materials of long fibers is usually in steps, characterizing the damage of each layer of fibers. As fibers could have 5 to 50 microns, the wear of the first layers or two ones will end the life of the triboelement. The nature of the fibers is natural, synthetic or combination. For tribological application, there are used carbon fibers, carbon nanotubes, glass fibers (if short, from tens microns to hundreds of millimeters but more efficient being those of several hundred microns to several millimeters), polymer fibers, more recently, aramid fibers [16]. Particles as reinforcement could have different shapes, from almost spherical (as for glass beads) to sheet-like or plaquettes (one dimension being very small as compared to the other two). A particular aspect of wearing polymeric composites or blends is the initially preferential wear of the softer material, the result being an increase concentration of harder particles or fibers; then the counterpart body will "attack" these harder materials; they could be fragmented and embedded into the soft matrix or they are torn off becoming wear debris, "traveling" in contact and induces oscillations of friction coefficient, but when their concentration increases, the component of abrasive wear becomes dominant and wear is greater; when the tribolayer loses its hard particles, the cycle is repeating. Thus, wear is a dynamic process, in steps, depending on local concentration of material constituents [9].

Figure 7 presents a process of consolidation of the tribolayers by embedding the fragments broken from short glass fibers a) PTFE +25% glass fibers, water lubrication, partial bearing (Ø60 mm, 30 mm width) and steel shaft: some glass fibers within the superficial layer cannot bear the local load and were broken; the fragments are embedded into the PTFE matrix [9].

Sometimes, adding materials in polymers could worsen the tribological behavior. For instance, too much concentration of glass fibers increases both and friction coefficient and wear (especially abrasive wear on both surfaces in contact).
A relation between mechanical characteristics in tensile tests and tribological one could be triky. Tensile strength could be improved by adding reinforcements, but strain at break is usually decreased. In sliding contact, a deformability ensures the contact conformability and in fluid lubrication helps generating the fluid film. But, even from 1979, Evans and Lancaster [35] reported that fibers in polymers have beneficial effects on wear and only rarely worsen this parameter. Some adding materials could have the role of a reinforcement but also could help for heat evacuating. A greater interest in using polymer composites and blends pointed out that the designer of the material has to do compromises that have to be accepted only by experimental results, models for predicting tribological behavior being difficult to establish in quantities [36].

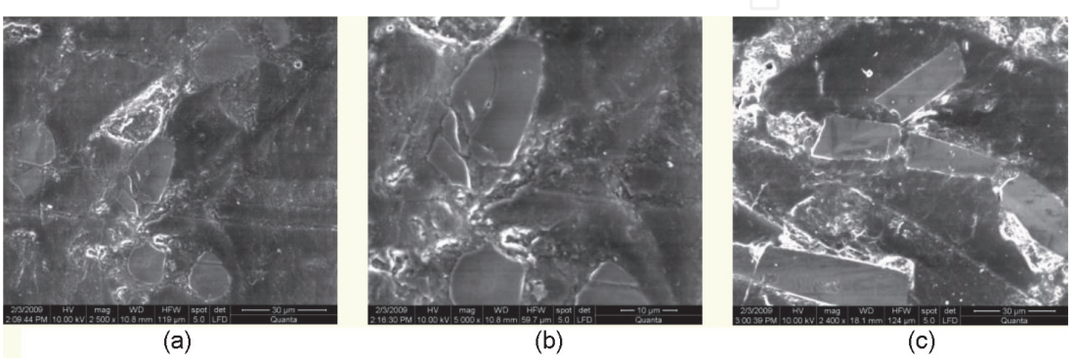


Figure 7.
Consolidation of the soft polymer matrix by glass fiber fragments, water lubrication, composites PTFE+glass fibers, large contact, partial bearing (120°) (Ø 60 mm x 30 mm width) [9]. (a) PTFE+15% glass fibers. (b) Detail of (a). (c) PTFE+25% glass fibers.

The addition of short carbon fibers (SCF) in a concentration from 5% to 20 vol% can improve the wear resistance of neat PEI remarkably, especially at high temperature and under high working pv-factor. The increased test temperature from room temperature to 150°C leads to a seven times increase in the wear rate of neat PEI and five times for the composites. SCF/PEI can withstand much higher pv-factor than that of neat PEI. When the pv-factor increased from 1 to 9 MPa m/s, the time-related wear rate of SCF/PEI almost linearly enhanced from 1.5×10^{-3} to 7×10^{-2} m/h. However, the wear rate of neat PEI increased from 0.214 to 3.42 m/h when the pv-factor was only increased from 0.25 to 3 MPa m/s. The micrographs of the worn counterface and specimens indicated that the sliding of neat PEI against metal counterface did not form a transfer film, and wear mechanisms varied from fatigue wear to plastic plowing at the increased temperatures. The presence of short carbon fibers helped generating transfer films both on the counterface and worn surface of specimens. The transfer film became more continuous with the increased test temperature. The composite wear was mainly undertaken by fibers [37].

Even if the process of wearing the polymeric composites comprises same stages, the aspect, dimensions and the concentration of added materials make the aspects of worn tribolayers very different. When sliding two bodies one against the other, the matrix is more deformable and the adding materials are like pebbles in the bottom of a shallow river. A partial detaching between matrix and particles/fibers could happen, the fibers change their position and the particles could roll or be dragged on the surface. The space left behind the hard element accumulate fine wear debris from both bodies or even from lubricant (when lubricating), stiffening the tribolayer. The random position of the hard materials and their agglomeration by wearing the soft material increase the probability of detaching conglomerates. This is why an optimum concentration of hard reinforcement in polymer-based material is around 15 … 25% and depends on the nature of reinforcement. For instance, 20 … 25% wt is an optimum in PTFE [9, 38, 39], but short aramid fibers are usually added at 10% wt due to the difficulty of injection molding as they block the injection nozzle [16]. As for particles with similar dimensions in all directions Georgescu [15] and Maftei [11] proved that 20% is the optimum concentration for glass beads of micron size.

If one analyzes the soft phases introduces in polymer-based materials, usually a solid lubricant, and with particular reference to PTFE [40] as solid lubricant, this concentration varies from 5 to 15% wt depending on the nature of the involved material. In PBT, the best concentration of PTFE was 5 … 10% the preferred criterion being the wear rate of the polymeric blend on steel [15].

3. Testing rigs, standard and non-standard testing methodologies

Laboratory tests, on simplified specimens, are useful for ranking materials, but these results could not be extrapolated to actual component, especially for polymeric materials.

Test campaign has to answer how the material pair behaves in a series of parameters

- lubrication regime,
- environment
- working regime (load, speed etc.),

- family of tested pairs of materials

In the ISO standard collection, the word wear is mentioned in 118 items, the test methology being adapted to the application, as, for instance, road and tire wear, implants, but for testing plastics there is.

ISO 7148-2:2012 Plain bearings — Testing of the tribological behavior of bearing materials — Part 2: Testing of polymer-based bearing materials.

ISO 6601:2002. Plastics — Friction and wear by sliding — Identification of test parameters.

ISO 20329 Plastics — Determination of abrasive wear by reciprocating linear sliding motion.

ISO 9352:2012 Plastics — Determination of resistance to wear by abrasive wheels.

ISO/DIS 7148–2 Plain bearings — Testing of the tribological behavior of bearing materials — Part 2: Testing of polymer-based bearing materials.

ISO/TR 11811:2012 Nanotechnologies — Guidance on methods for nano- and microtribology measurements.

The selection of tests necessary for assessing tribological behavior of a material pair including polymer-based materials depends on

- the research level (laboratory, application under development, design of new materials, failure investigation),

- the characteristics of the tribosystems, distinct regimes of sliding wear are "severe" and "mild".

- the actual working conditions

Many different approaches could be seen in literature for assessing the tribological behavior of a system, differentiate in scale and complexity of the tested system. A logical order will be.

Laboratory tests → Model tests→ Component bench tests → System bench tests→ Machine bench test→ Machine field test [41, 42].

In the same direction there are increasing complexity and costs, but first types of tests have increasing control and scale investigation and flexibility.

Depending of the novelty degree of the solution, one or more of the stages mentioned above could be omitted. New materials and original design solutions ask for all, but they have to be solved quite rapidly in order to gain the market.

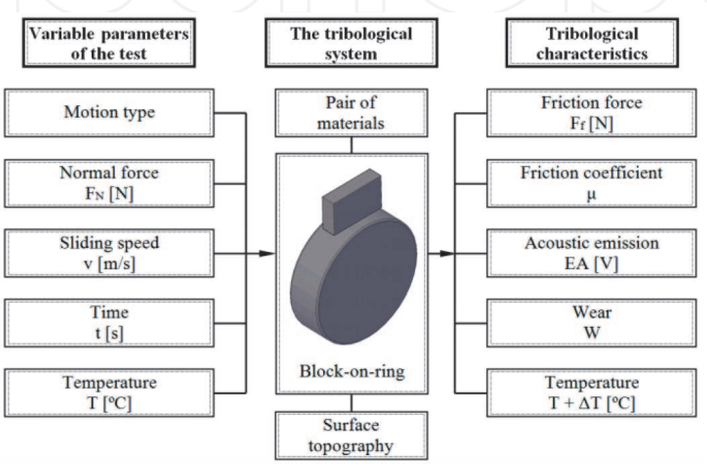


Figure 8.
Characteristics and relevant parameters for the tribotester block-on-ring [15, 16].

A testing campaign is suggestively given in **Figure 8**. This plan was elaborated by Georgescu [15], but also used by Botan [16]. It was the result of consulting adapted from [42]. Polymeric blocks have the dimensions (10 mm x 16.5 mm x 4 mm). The values are quite small and it is very probably not to have actual component of such dimensions, but such a test campaign is very useful for ranking the materials and to investigate modifications in the tribolayers by the help of electron scanning microscopy, AFM, Raman microscopy as the test specimens are small.

4. Tribological parameters and evaluation of experimental results

The set of tribological parameters are characterizing the materials Laboratory tests, on simplified specimens, are useful for ranking materials, but these results could not be extrapolated to actual component, especially for polymeric materials.

When designing a test campaign, for assessing the tribological behavior of a material pair, the tribosystem has to be identified as one in **Figure 9** [42], this simplified initial system being tested at laboratory level with as many as possible parameters closer to those from actual application.

The coefficient of friction is a convenient method for reporting friction force, since in many cases F_f is approximately linearly proportional to F over quite large ranges of N. The equation, known as Amonton's law is

$$F_f = \mu F \tag{1}$$

where the value of μ depends significantly on working regime (lubricated or not), the composition, topography and history of the tribolayers, the environment in which they are working and the loading conditions. Ashby [43] gave a suggestive diagram, positioning the polymeric materials with lowest wear rate, but wear rate values could scan o two-order of magnitude. He also suggests by this diagram that wear rate field could be extended, especially towards low values by filling the polymers. A special position is noticed for PTFE (**Figure 10**), unique polymer as tribological behavior (the lowest friction coefficient, high wear rate, high working temperature and very resistant in aggressive media).

Usually, when a component if made of polymeric material, the other is harder, made of steel, but recently contact could be between the same polymeric materials of different. Thus, friction has to be treated for these cases.

In the case of harder counterpart, the friction polymer-metal has the following components: plowing as a form of abrasion with larger elasto-plastic deformation and micro-cracks and adhesion [3, 8]. These processes are severely depending on many factors including the hardness and asperity shape of the counterpart, contact

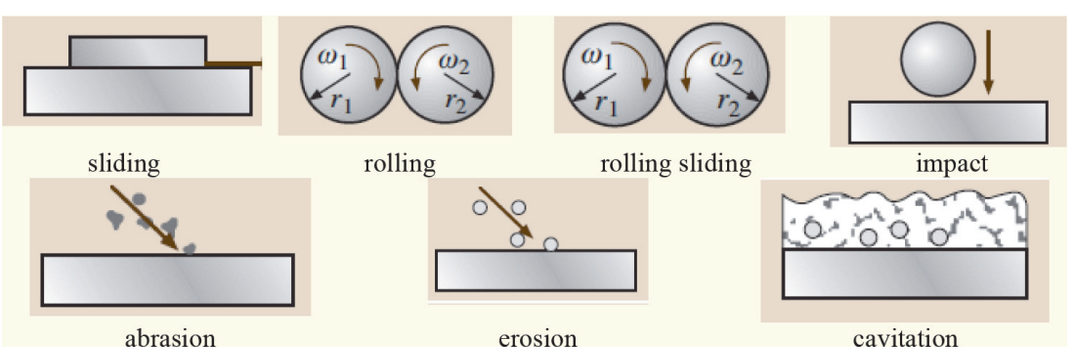


Figure 9.
Testers for assessment of tribological behavior of polymers and polymer composites [42].

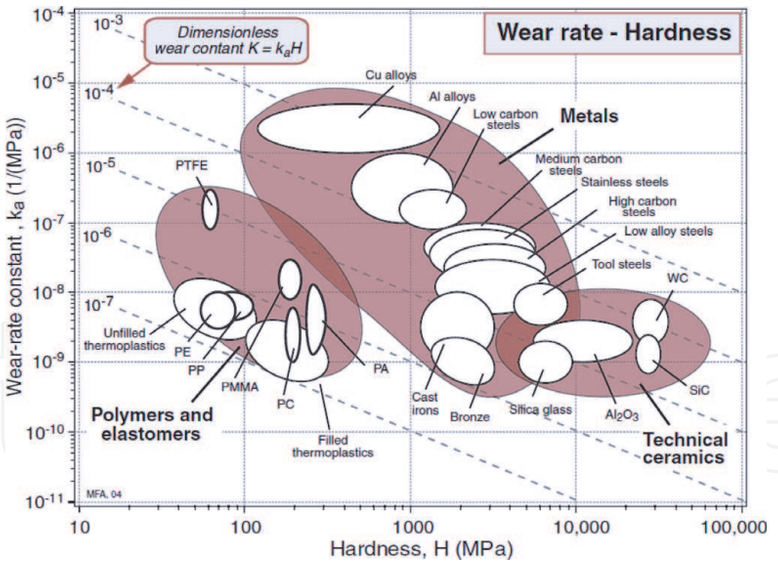


Figure 10.
Positioning of polymers and polymer composites in a space hardness-wear rate constant [http://www.mie.uth.gr/ekp_yliko/2_materials-charts-2009.pdf] [43].

load, speed, temperature. This component of friction could be reduced by introducing a lubricant in contact or/and by re-design the system to have rolling or rolling-sliding motion and by an adequate cutting (usually grinding, honing) of the metallic counterpart.

The adhesion is present both in static friction and dynamic friction of polymeric materials: at the interface motion generates shear and deformation of a very thin layer of the polymeric material, directly in contact with the counterpart. As adhesion and transfer on the counter part are developed in steps, the friction loss, and consequently, the friction coefficient will vary in time, especially for sliding contacts.

Values of friction coefficient are given by producers, researchers but they are depending on test conditions. Thus, they could give a ranking of the tested materials under the same conditions, but they could not be the same with actual components. Sometimes, especially under low load, negative values of μ may be noticed: they are rather artificial, due to contact separation and inertia of the tester components; values of μ greater than 1 are physically logical, especially in material processing, in the interaction between a car tire and a dry road. Sampling could vary depending on the gauge measuring the resistance force. Researchers usually use a moving average to draw the curve of friction force or coefficient in time. For instance, the curve in **Figure 11** was done by moving average of 200 values with sampling 2 values per second. But extreme values are also important as they limit a range that could explain failure mechanisms as adhesion or local melting, especially for polymeric materials.

In most cases, a single value of coefficient of friction is not adequate. This can be seen from the examples in **Figure 11**, depicting the evolution of friction coefficient for three sliding distance. The aspect of evolution is kept for PBT, but these three tests gave values between 0.16 … 0.19, with stable evolution, a characteristic of polymer sliding as compared to metal–metal contacts.

The evolution of COF in **Figure 11** points out that, for polymer on steel in dry regime, it is less sensitive to time, but these conclusion has to mention the time range for which the researchers had obtained this results, here for 2500 … 7000 m.

Czichos [41] modeled the evolution of COF for a dry regime in four stages: 1-increasing trend as the surfaces accommodate by wear, 2 - shorter stage of maximum values of COF, 3 - decrease of COF by the generation of a tribolayer favorable

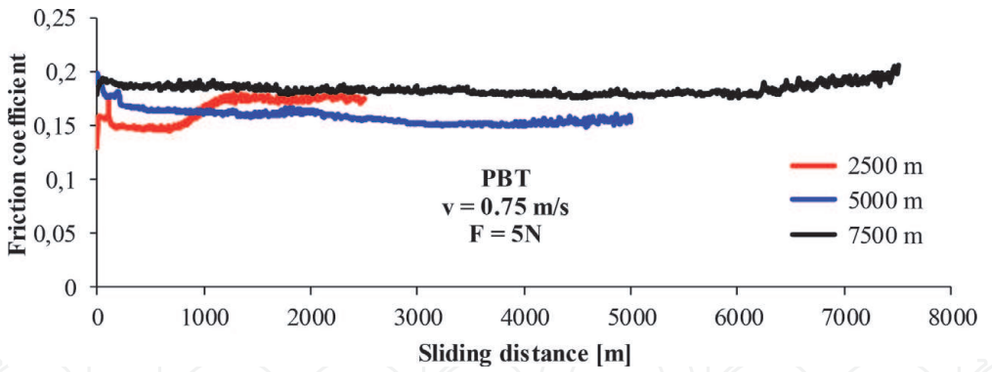


Figure 11.
Friction coefficient for three tests block-on-ring, with different sliding distances [15].

to reduce friction, for instance, a soften or molten layer of polymer, transfer films on harder surface etc. and the abrasive wear and deformation intensities decrease, 4 - stable evolution of friction. For polymer on steel or even on themselves, the authors will add a stage, 5 - slowly or sudden increase of COF meaning worsening the surface in contact due to severe wear, fatigue etc., in many times this increase announcing the life end of at least one triboelement (**Figures 12** and **13**).

Too low load makes the friction coefficient to have higher oscillations as superficial layer of the polymer is not compresses and hard asperities will easier tear up micro-sheets or plaquettes. As the load increases, the tribolayer is compacting and the energy loss by tearing decreases. This phenomenon of oscillating the friction coefficient in dry contact of polymers have been notice also by Jones in 1971 [44]. Higher concentration of reinforcement increases the friction coefficient and makes its evolution wavy (high amplitude could mean an increase of the glass bead concentration in the tribolayer and low values could happen when the tribolayer is richer in polymer.

Convergence of the curves for higher velocity (in **Figure 13**, for sliding speed of 0.5 m/s and 0.75 m/s) means that friction process is similar, very possible involving

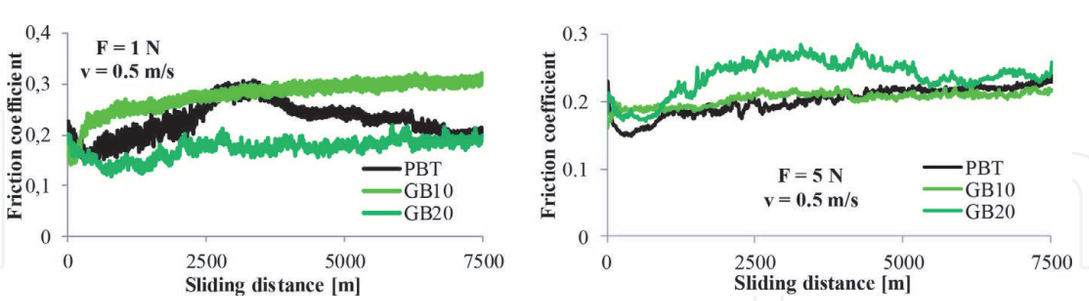


Figure 12.
Influence of load at the same sliding velocity (GB10 - PBT +10% glass beads, GB20 - PBT +20% glass beads) [15].

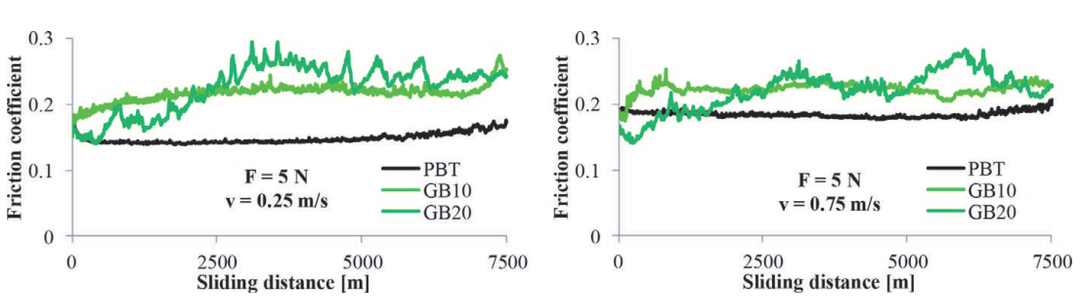


Figure 13.
Influence of sliding velocity under the same load [15].

a very thin soften/melted layer of polymer. This is obvious in another study [11], using pin-on-disk tribotester.

This example point out the influence of the nature of polymeric materials: the composite (the composites with hard micro-particles in a PBT matrix have higher and rough aspect of the curve, the blends PBT+ PTFE having lower values even the polymer PBT, considered a polymeric blends with soft drops of PTFE in PBT matrix). **Figure 14** presents the influence of sliding velocity on the friction coefficient, and the curves in **Figure 15** show the friction coefficient evolution in time depending on the highest load and velocity. The last plot is given only once as it could be related both to load and velocity dependence. The abbreviations for the materials are: PF5 - PBT + 5% PTFE, PF10 - PBT + 10% PTFE, PF15 - PBT + 15% PTFE). The composition of the hybrid composite GB10 + PF10 (having 10% glass beads and 10% PTFE) makes the friction coefficient to be higher at low velocity (0.25 m/s), but for the other two tested velocity, this tribological parameter evolves in a similar manner, but with higher oscillations, probably because of hard glass beads in the tribolayer (**Figure 16**).

Wear is not only a process of material removal in moving contacts, but a more complex one, defined recently as damage of the solid bodies caused by working or testing conditions, generally involving progressive loss of material, elasto-plastic deformations, tribo-chemical reactions caused by local pressure and heat generation in friction and their synergic interactions [8, 20]. In majority cases, the relative motion is intentional: for example, in plain bearings, pistons in cylinders, automotive brake disks interacting with brake pads, or in material processing (cutting, injection, rolling or extrusion). But in some cases, there are also undesired motion(s), resulted because of particular working conditions, as in the small cyclic displacements, known as fretting, produced by vibrations, elasto-plastic and tribological behavior of components in contact. If solid particles are passing through the contact, as contaminants in lubricant or, intentionally, as abrasive material for processing, then they will have a tremendous influence on wear process and, thus, on system durability.

Wear is a complex process, quantified by the volume or mass of removed material, from each body in contact, the change in some linear dimension after a time period of functioning. Thus, wear is obviously a function of material pair, working time and conditions and it is related to a particular tribosystem (materials, dimensions, shapes and working conditions).

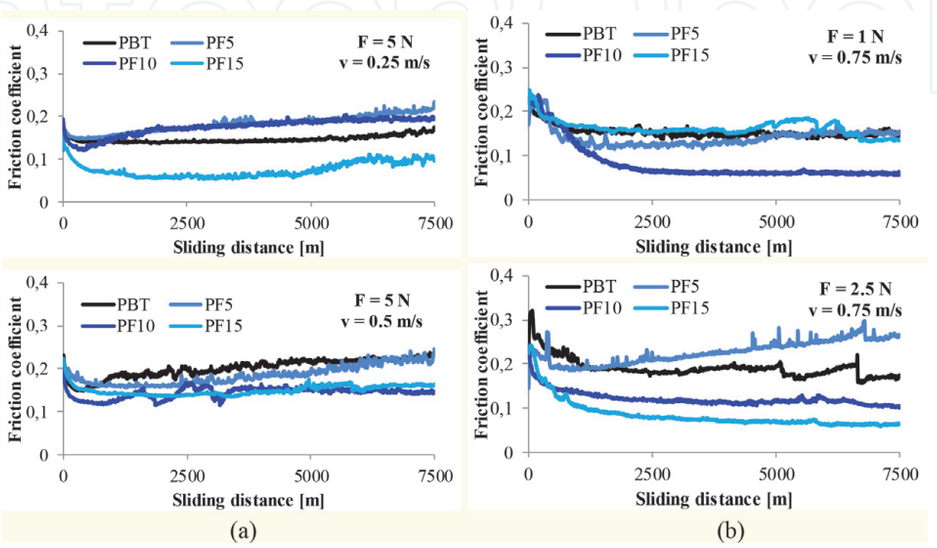


Figure 14.
Influence of sliding velocity, at F = 5 N, for PBT, PF5, PF10, PF15 [15].

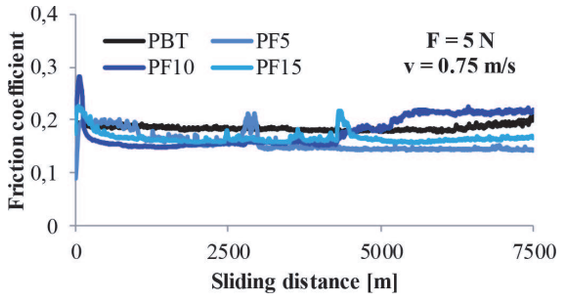


Figure 15.
Influence of load, at v = 0,75 m/s, for PBT, PF5, PF10, PF15 [15].

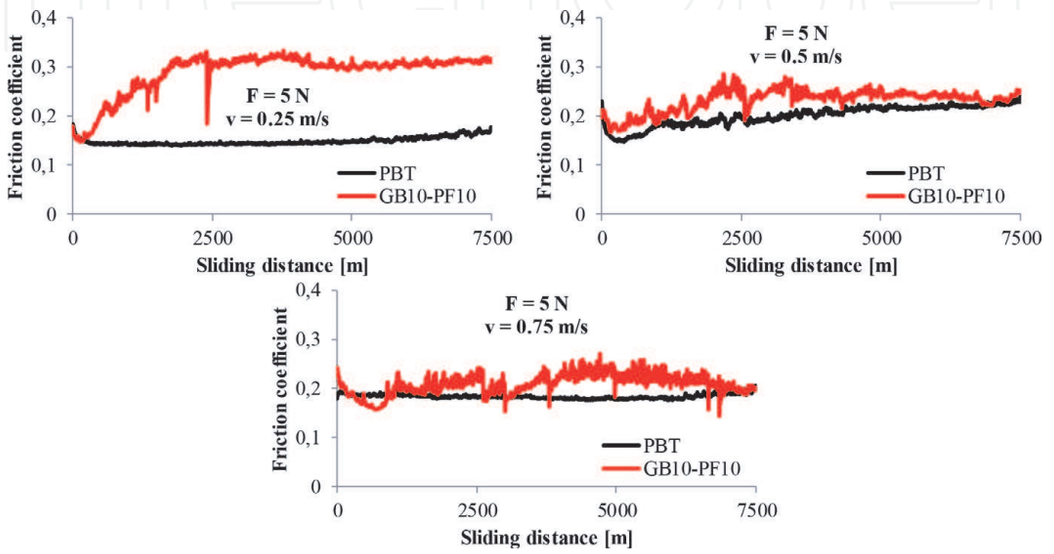


Figure 16.
Evolution of the friction coefficient for PBT and a hybrid composite (PBT + 10% glass beads+10% PTFE) [15].

In some cases, material may be lost from both triboelements, or significant transfer of material may occur between the triboelements, and particular care is needed in both measuring the magnitude of wear and describing the damage it generates (material removals, abrasion, adhesion, transfer, plastic deformation, fragmentation and mixing the constituents of the tribolayer changes in the topography, the last one being investigating by the help of advanced non-contact profilometers [45].

The wear of polymeric material implies an aspect that is of interest only in pairs with a polymeric material: melting wear. A part of heat generate by friction is transferred to the polymeric materials and as thermal conductivity of polymers is low, a very thin layer could soften or even melt, the material latent heat of melting imposing a temperature limit in dry contacts. Stachowiack and Batchelor [46] described the scenario of temperature evolution in contact with a polymeric material (**Figure 17**). Similar observations are done by Briscoe and Sinha in [8], relating the polymer softening and its nature to transfer process on the harder counterface.

Experiment work validated this process of keeping constant the temperature in contact when a triboelement is made based on polymers. In order to support this conclusion, two studies are presented. First one is shortly presented in **Figure 18**. A cylindrical pin made of bearing steel is sliding against a disk made of composites PA + 10% wt glass beads +1% black carbon [11]. The thermo-image in left side presents the positions and their codes where the temperature was recorded with a thermo-camera. The temperature evolutions in time for these three points re given in the right. It is obvious the tendency of maintaining the temperature almost

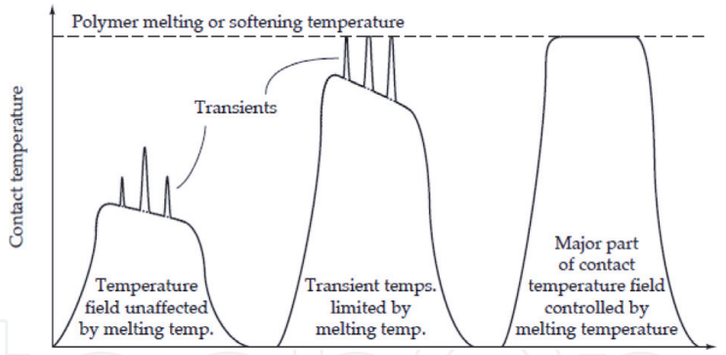


Figure 17.
Evolution in time of temperature of polymeric surface in sliding contact [46].

constant for v = 0.5 m/s and v = 1 m/s. As for the highest tested velocity, the plateau is zigzagged at almost regular time period. This could be explained by the polymer softening or even melting, followed by easier removal from the tribolayer, enrichment in glass beads of the tribolayer, with higher friction and thus, generating heat and rising the temperature. When the glass beads are embedded in the remaining matrix or removed, the temperature would reach a minimum.

Another study [16] for emphasizing the importance of testing composites with polymer matrix has the results obtained on block-on-disk tribotester (**Figure 19**). The block is made of composite with 10% short aramid fibers (Twaron, grade, 225 μm in length see **Figure 5c**), with two different matrices: PA and PBT and the ring is the outer ring of a taped rolling bearing (the quality of rolling bearing ring keeps contact the influence of the counterbody in sliding). Analyzing **Figure 20**, the friction coefficient for PAX on steel has a steady evolution, in narrow ranges, for low loads (F = 5 N and F = 15 N) but for F = 30 N, for higher velocities, it increases and becomes steady at higher values, around 0.3. Temperature is steady for the same low loads, but it increases with different slopes for highest load. A too low load on polymer-based material - steel could rise COF and temperature in contact because the hard body does not contact the polymeric tribolayer enough and thus, the wear has a more intense abrasive component, tearing-off easier the polymer.

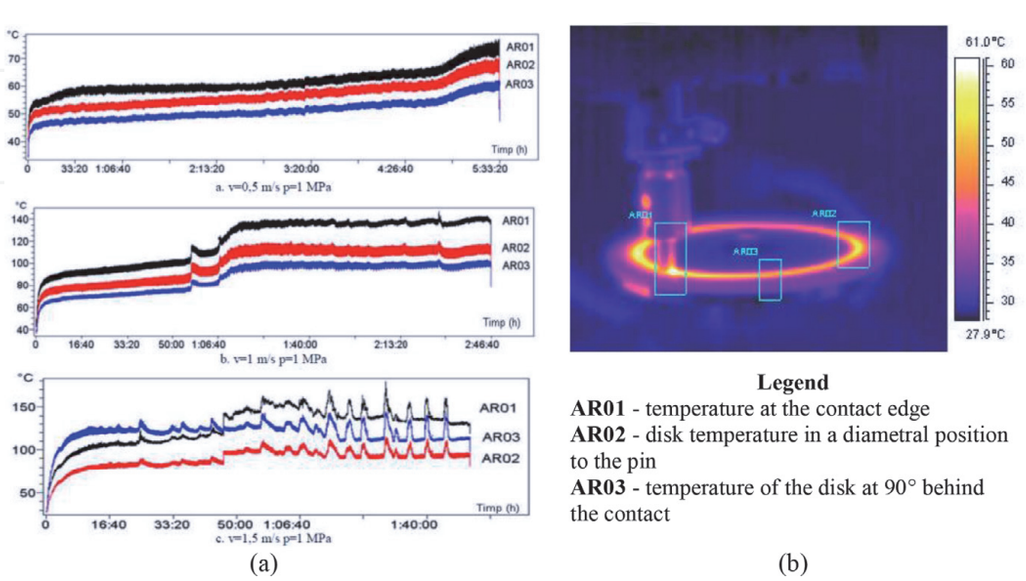


Figure 18.
Temperature evolution in time (a) for pin-on-disk tester, pin made of hard steel and disk made of PA + 10% grass beads + 1% black carbon, dry sliding for 10000 m and a thermal image during the test (b) (the rotation of the disk is clockwise) [11].

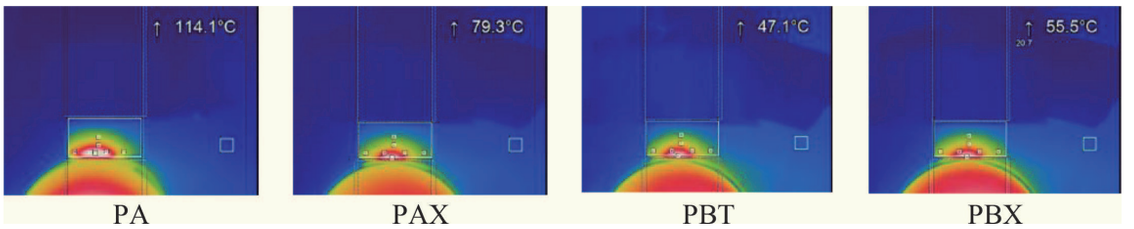


Figure 19.
Images of thermal recordings of the temperature at the end of the test, for temperature at the contact edge, F = 30 v = 0,75 m/s (block made of PA- polyamide, PAX - polyamide +10% aramid fibers +1% black carbon, PBT - polybythylene therephtalate, PBX - PBT +10% aramid fibers +1% black carbon) [16].

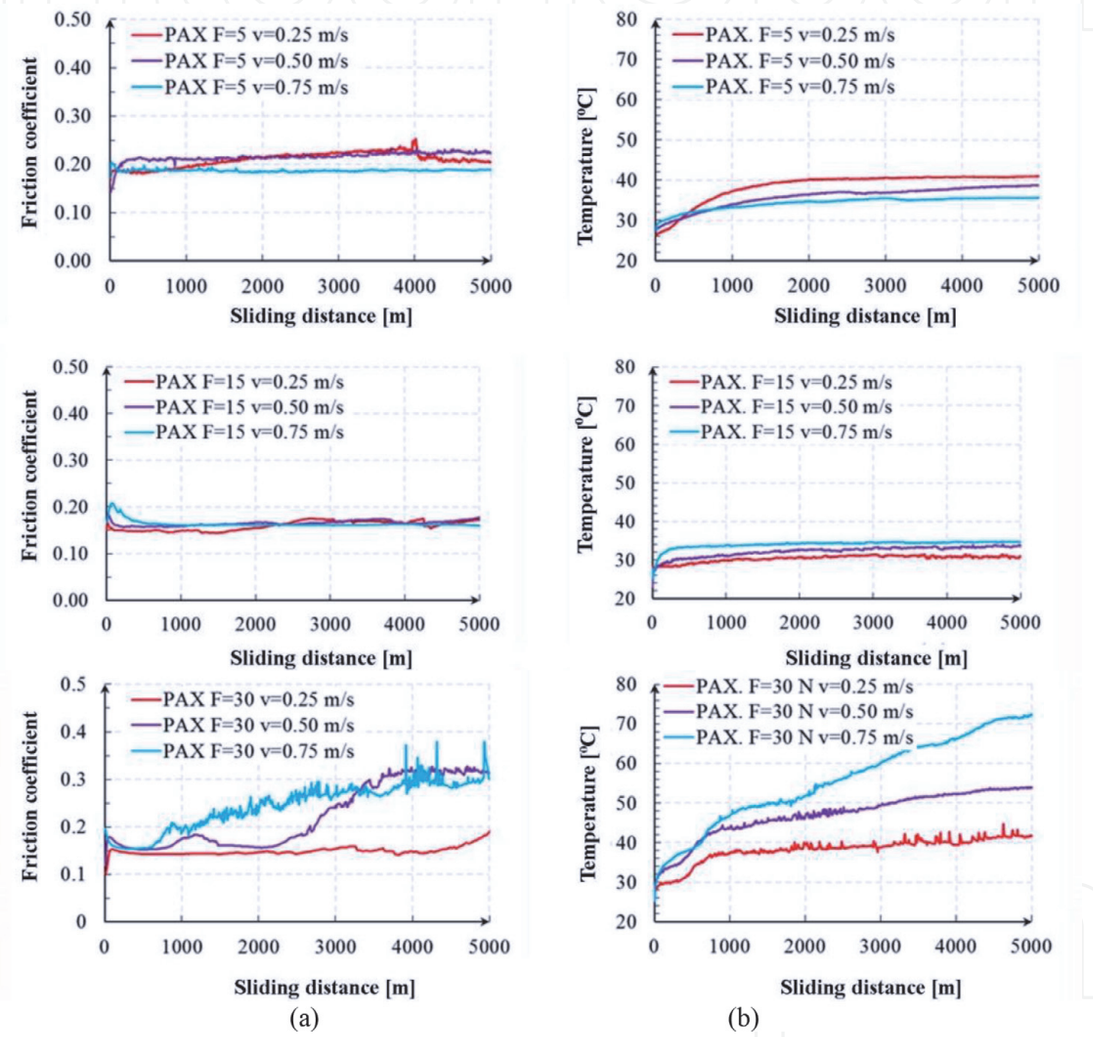


Figure 20.
Evolution of friction coefficient and temperature at the contact edge in time, depending on load, sliding velocity, for a sliding distance of L = 5000 m, block made of PBT +10% aramid fibers, L = 5000 m, block made of PAX (PA6 + 10% aramid fibers) [16].

The combined analysis of two tribological parameters could reveal a qualitative change of the working regime. For instance, analyzing COF and temperature at the contact edge (**Figure 20**),

- a too low load and sliding velocity make the temperature rising due to abrasive wear (more intense under low load)
- a higher speed makes the temperature curve higher for v = 0.75 m/s, but the COF is kept low meaning a softening process happened,

- a too high load makes the temperature to have a slope, greater as velocity increases; a mild regime (thus, a favorable regime) will keep the temperature constant in contact as for tests under F = 15 N. The severe regime is marked by high oscillation of friction coefficient or even a constantly increased value and also by the same shape of the temperature curves.

Comparing curves in **Figure 20**, regimes with F = 30 N and high sliding velocity (v = 0.5 … 0.75 m/s) could be considered as severe because they do not make tribological parameters as friction coefficient and temperature in contact, stable.

The composite with PBT matrix with the same adding materials (10% short aramid fibers and 1% black carbon) has a similar evolution of COF, but temperature increases only for the extreme tested regime (F = 30 N, v = 0.75 m/s).

The applications involving the friction couple polymeric material - metallic counterpart are preferred by mechanical requirements of the design solution and the better tribological behavior by monitoring and measuring a set of tribological characteristics (wear, friction, temperature in contact, changes in materials' structures etc.) as compared to sliding polymers against themselves (**Figure 21**).

Wear process of polymeric materials are characterized by a transfer film, generated when sliding against a harder surface, strongly influencing on the tribological behavior of the system [8].

A favorable transfer film should be continuous, very thin and regenerating without inducing troubles in the working systems. This is the ideal transfer film of a

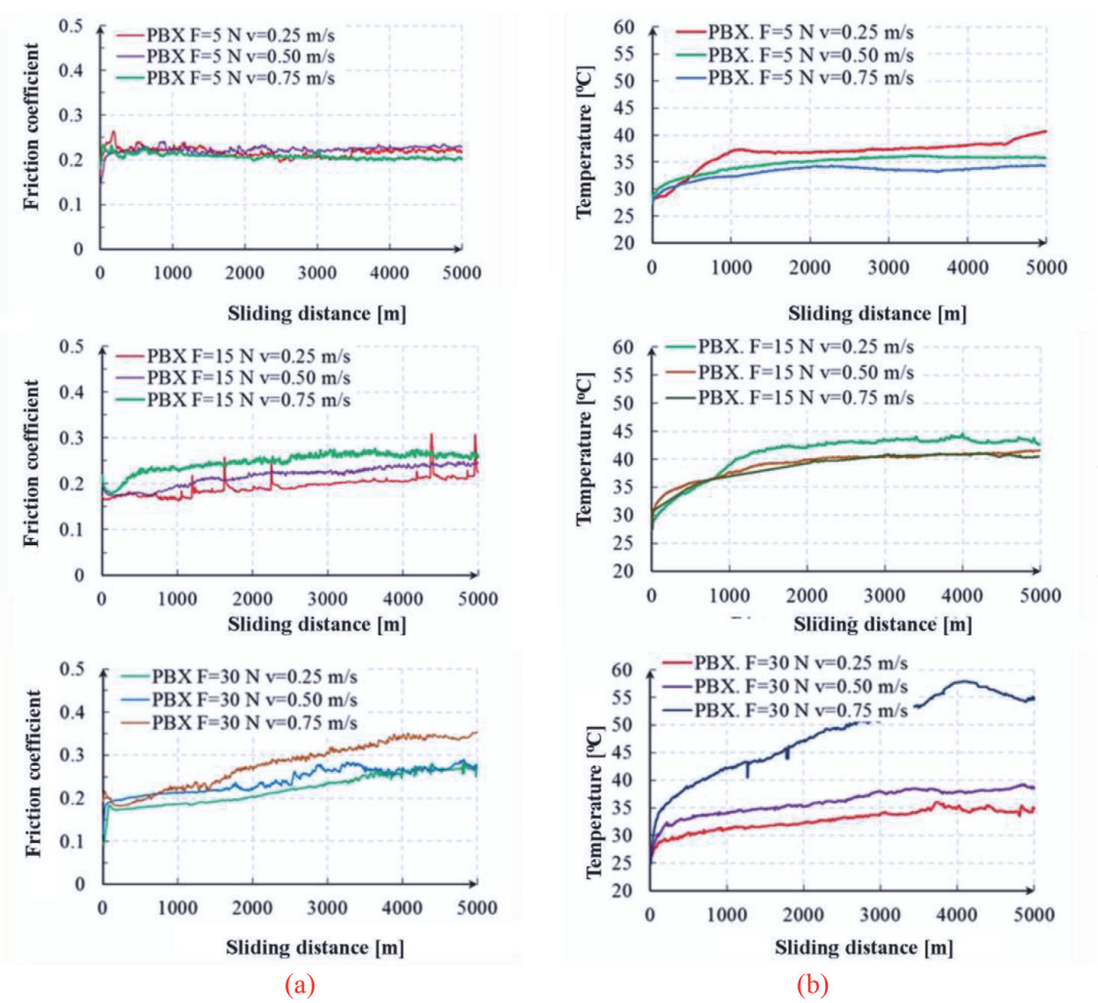


Figure 21.
Evolution of friction coefficient and temperature at the contact edge in time, depending on load, sliding velocity, for a sliding distance of L = 5000 m, block made of PBX (PBT +10% aramid fibers) [16].

polymeric material but, actually, there are two types of polymers, those generating an almost continuously transfer film as high density polyethylene (HDPE) and ultra-high-molecular weight polyethylene (UHMWPE), and those that form lumps or islands, more or less regular. Transfer process is influenced by contact temperature and texture of the counterpart. Only few polymers have only a mechanical component of the transfer film (again, PTFE and UHMWPE have to be given as examples) and polymers that could chemically interact with the metallic surface.

Myshkin et al. [7] pointed out that the dependence of friction coefficient with velocity has different shapes depending on the polymer sliding on steel or on itself, and even for the same polymer, the curve depends on temperature of the environment. At low velocity ($10^{-3} \ldots 10^{-2}$ m/s), friction coefficient has an almost constant evolution, but at higher speed, its evolution could be with velocity could be parabolic, with minimum when the material is softening or has a thin melt layer, than it could increase. The conclusion of this work is that tests in the same conditions as the application are tremendously necessary for a reliable working of the tribosystem involving polymer-based materials in order to correct assess the power loss by friction and to prevent component failure by frictional heat.

The wear rate can then be defined as the rate of material removal or dimensional change per unit time, or per unit sliding distance. Because of the possibility of confusion, the term "wear rate" must always be defined, and its units stated. It is usually the mass or volume loss per unit time.

The Archard model of sliding wear [47] leads to the equation:

$$w = KW/H, \tag{2}$$

where w is the volume of material removed from the surface by wear per unit sliding distance, W is the normal load applied between the surfaces, and H is the indentation hardness of the softer surface. Many sliding systems do show a dependence of wear on sliding distance which is close to linear, and under some conditions also show wear rates which are roughly proportional to normal load. The constant K, usually termed the Archard wear coefficient, is dimensionless and always less than unity. The value of K provides a means of comparing the severities of different wear processes.

For the tribotester block-on-ring the wear parameter that reflects well the behavior of the materials could be the linear wear rate

$$Wl = \Delta Z/(F \cdot L)\ [\mu m/(N \cdot km)], \tag{3}$$

where ΔZ is the change in distance between ring and block at the end of the test, F is the normally applied load and L is the sliding distance. **Figure 22** presents test parameters, as recorded by the tribometer UMT-2, including friction coefficient (COF), wear depth (Z).

For pointing out wear parameters in a tribosystem with polymer-based material (s), the same two cases are analyzed (**Figure 23**).

A study has another objective [16]: to assess the tribological behavior of two polymer matrices, PA and PBT, with the same concentration of reinforcement, 10% wt short aramid fibers (Twaron, 225 microns as average length). There were measured several tribological parameters, average values of friction coefficient (COF, **Figure 24**), wear rate (**Figure 25**) and maximum value of the temperature at the contact edge (**Figure 26**). Wear rate in **Figure 25** was calculated as

$$W = \Delta m/(F \cdot L)\ [mg/(N \cdot km)], \tag{4}$$

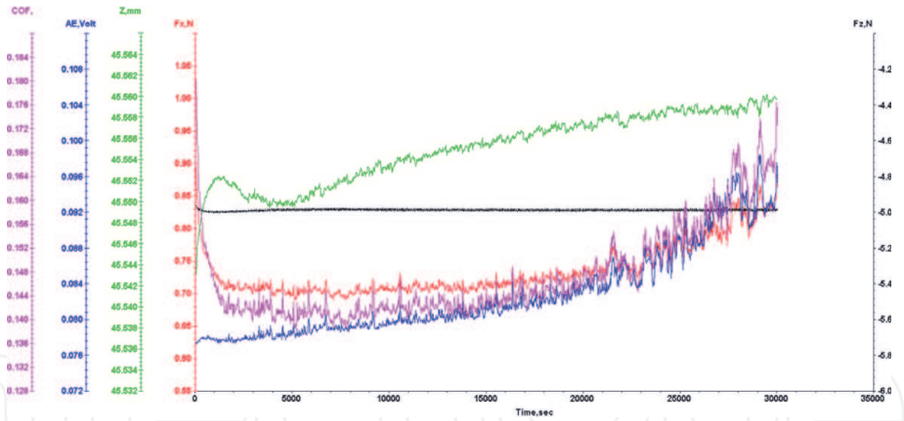


Figure 22.
Example of parameters monitored in actual time real on the tribotester UMT-2, block-on-ring test, block made of PBT, ring made of steel (100Cr6), F = 5 N (= Fz), v = 0,25 m/s, L = 7500 m, COF –friction coefficient, Fx – Resistant force (friction), AE – Acoustic emission, Z – Wear depth (linear wear) (linear change between ring and block), Fz – Normal load [15].

where Δm is the mass loss of the block, L is the sliding distance and F is the applied load in contact.

Temperature in contact is very important in tribosystem with one or both elements made of polymeric materials as a jump in contact temperature of less amount as for metals (even 10°C) could change their mechanical and thermal properties, could even change the chemical organization of the molecular chains; the power dissipated in the contact is given by (μ·F·v) where μ is the friction coefficient, F is the normal load and v is the sliding velocity. The local temperatures in the contact areas can therefore become much higher than the bulk temperatures. This factor needs to be considered when designing wear tests or interpreting test results.

In Botan's study [16], neat PBT had a very good tribological behavior (being analyzed, average values of COF during 5000 m of sliding on steel, low wear as compared to PA) but adding 10%wt short aramid fibers in PBT substantially improves wear resistance. Thermal monitoring of the contact edge allows for ranking the tested materials having the temperature as criterion (**Figure 26**).

In study from 2012, Pei et al. [12] present the tribology of three polymers, considered as high-performance materials, introducing for evaluating the product pv (p being the average pressure in contact and v the sliding velocity). This parameter has to be used with precaution. Comparison should be done for the same tribosystem (dimensions and shapes) and under the same testing conditions. It is not recommended to extrapolate the results outside the investigated parameters. From **Figure 27**, one may notice that PPP grades exhibited low wear resistance as compared to PEEK and PBI had the lowest wear rate, due to its high value for heat resistance and very low decrease in mechanical characteristics under higher temperatures.

Obviously, in dry regime friction coefficient of a polymer on steel is lower than that for steel-on-steel and long and aligned carbon chain (as in PTFE and PE, even PA) will give lower dynamic friction coefficient, around 0.2 … 0.3, lower for PTFE, but polymers with higher mechanical characteristics as PPS and PEEK will have this parameter higher 0.3 … 0.5. Wear rate exhibits values that could not be deduced from the mechanical and structural characteristics. For instance, in **Figure 28**, the lowest wear rate among tested polymers under the same conditions was obtained for PA6, and wear rate increases from this to PI, PPS, PE-UHMW till PEEK, but high values were obtained for POM and PTFE.

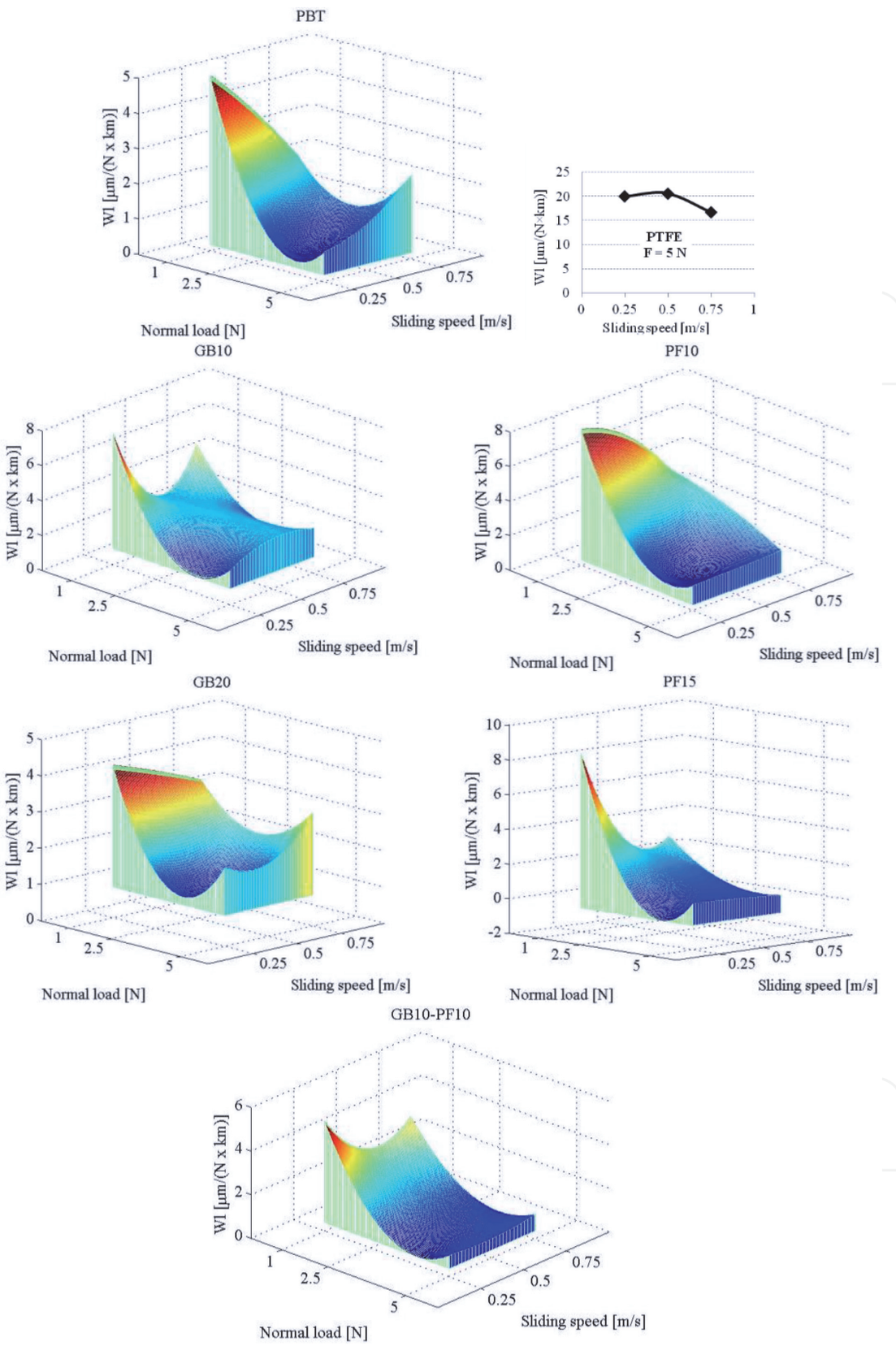


Figure 23.
Linear wear rate of the blocks made of polymer-based materials.

Worn surfaces and the debris resulting from wear, may be examined for several reasons:

- to study the evolution of wear during an experiment, or during the life of a component in a practical application,

- to compare features produced in a laboratory test with those observed in a practical application,
- to identify mechanisms of wear,
- (by studying debris) to identify the source of debris in a real-life application.

Figure 29 presents two virtual images, reconstructed with SPIP The Scanning Probe Image Processor SPIPTM, Version 5.1.11/2012, from a study done by

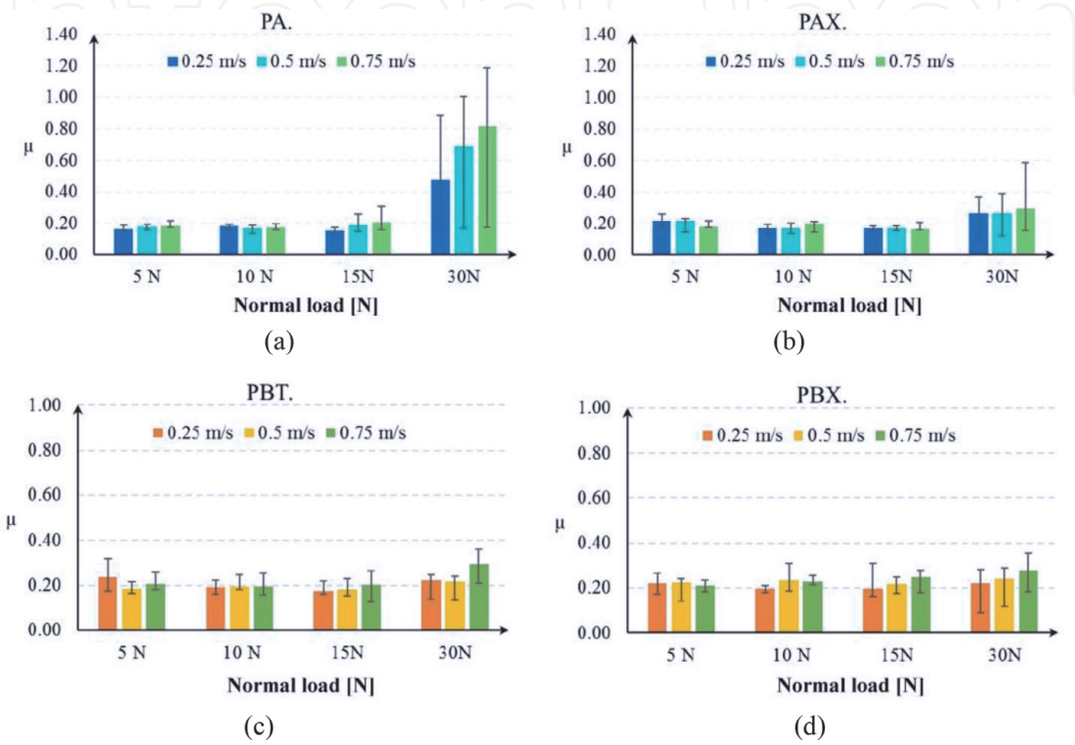


Figure 24.
Average values for COF for 5000 m of dry sliding on steel (same scale for PA and PAX and PBT and PBX, respectively) [16].

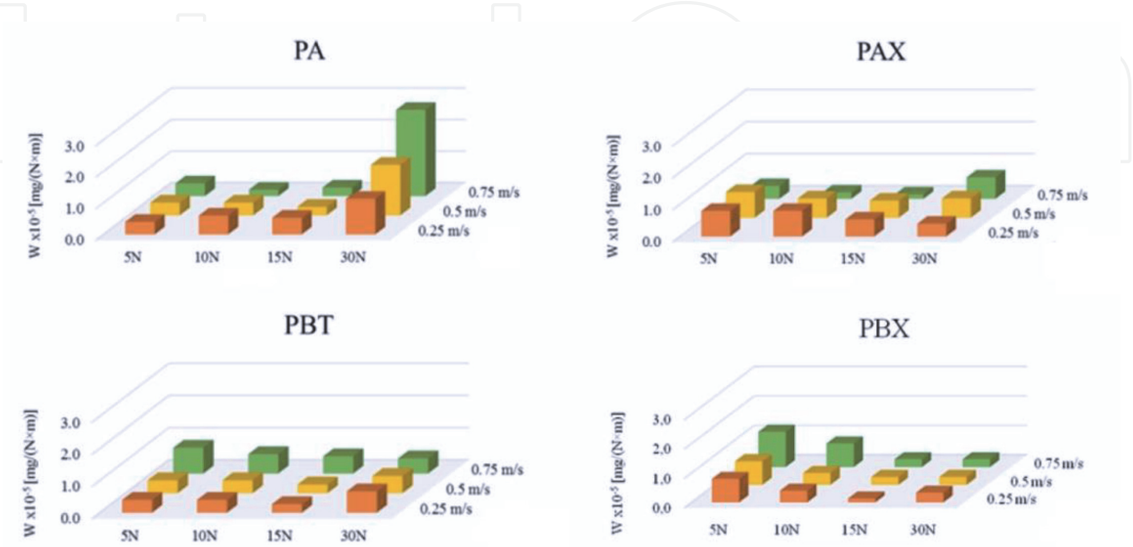


Figure 25.
Wear rate of the block as a function of load (in N) and sliding speed (m/s), obtained on block-on-ring tester, dry regime, for blocks made of polymers (Polyamide 6 - PA and Polybuthyleneterphtalate - PBT) and their composites with 10% short aramid fibers (PAX and PBX).

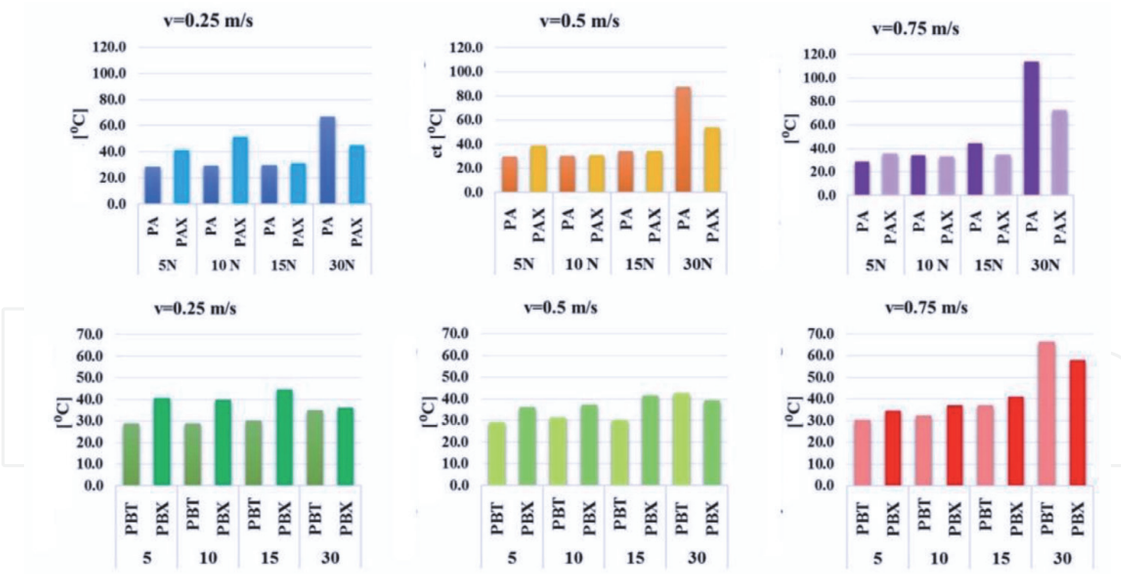


Figure 26.
Maximum value of temperature at the contact edge, for all four tested materials in [16] (material codes as in previous figure).

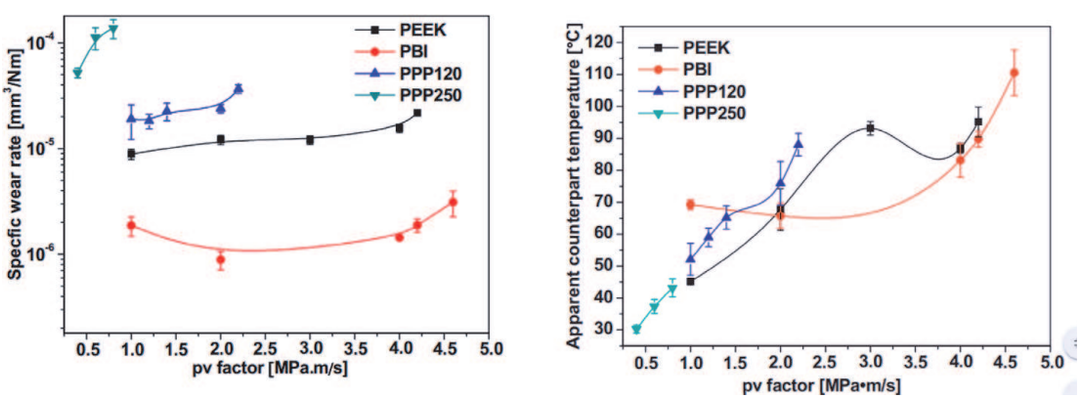


Figure 27.
Specific wear rate of polymer sliding on steel and counterpart temperature for [12].

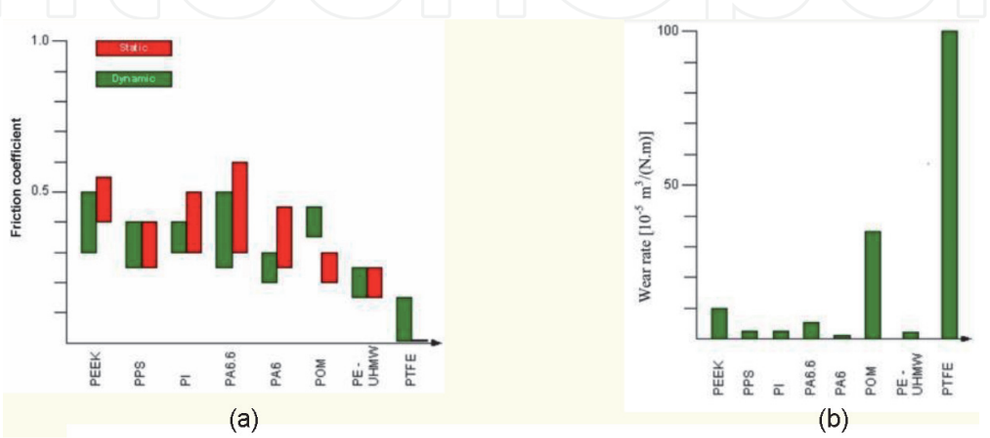


Figure 28.
Two tribological parameters for polymer in dry sliding on steel [http://www.appstate.edu/~clementsjs/polymerproperties/$p$lastics_$f$riction$5f$w$ear.pdf]. (a) Friction coefficient. (b) Wear rate [48].

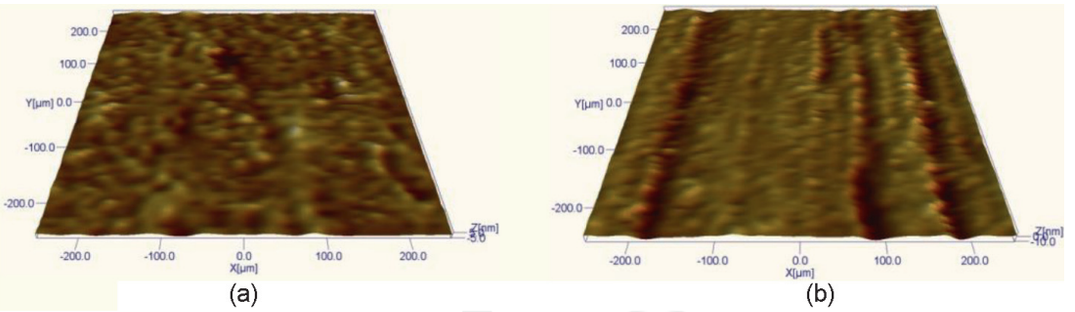


Figure 29.
Virtual images of block surfaces made of PBT + 20% glass beads. (a) Initial surface. (b) Used surface (F = 5 N, v = 0,75 m/s, L = 7500 m) [15].

Georgescu [15], pointing out initial surface (a) and traces as result of abrasive wear on the composite.

After testing, the worn surface quality of the composite with only 10% glass beads was better, meaning a lower value for Sa, Sz (**Figure 30**). In tribological evaluation a ratio Sz/Sa, bringing together an averaging parameter with an extreme one (Sz) is important because singular or rare high peaks have a great influence on the tribological behavior, especially for composites with hard fillers. Adding micro glass beads in PBT increases the amplitude parameters (these are plotted for v = 0 m/s, in **Figure 30**). Ssk has high positive values for 20% glass beads in PBT, but the polymer and the composite with only 10% glass beads have lower values, oscillating between 1 and − 1. If Ssk < 0, it can be a bearing surface with holes and if Ssk > 0 it can be a flat surface with peaks. Values numerically greater than 1.0 may

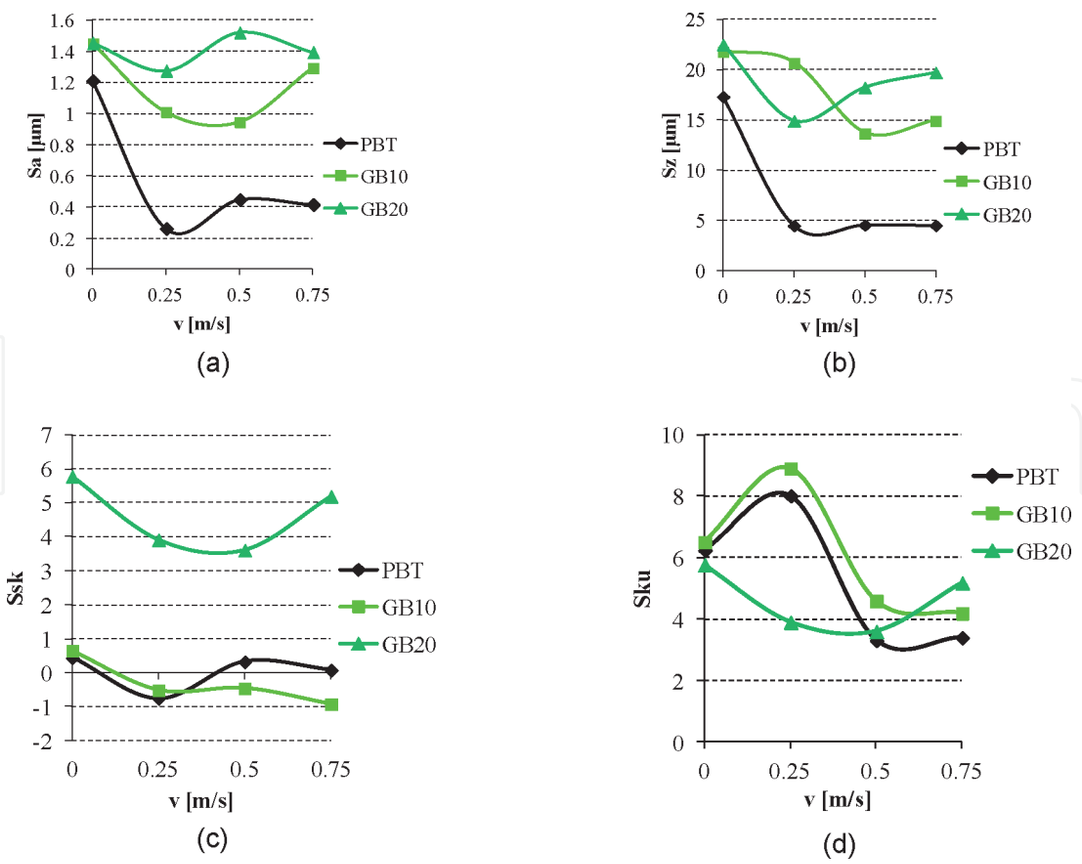


Figure 30.
Roughness for worn surfaces of the block made of PBT, PBT + 10% glass beads (GB10) and PBT + 20% glass beads (GB20). (a) Sa- roughness average. (b) Sz - peak-peak height, the difference between the highest and lowest point in surface. (c) Surface skewness, Ssk, or the asymmetry of the height distribution histogram. (d) Surface kurtosis, Sku, or the "peakedness" of the surface topography [15].

Parameter	Information, unit
Load (normally applied), constant or variable	N
Sliding speed	m/s
Pair of materials	Composition, phases, structures
Temperature (environment and in contact)	The second is difficult to measure
Type or relative motion	Sliding, rolling, combined motion, small oscillations, impact
Contact type	Conformal, non-conformal, volumes of the triboelement
Particularities of tribosystem (if the case) abrasive/erosive particles	Material, shape, size and distribution
Contact dynamics	Stiffness, damping, inertial mass

Table 2.
List of important parameters that influence the tribological behavior [42].

indicate extreme holes or peaks on the surface, as for the worn surfaces of composite PBT + 20% glass beads. For v = 0.50 m/s (**Figure 30**) and v = 0.75 m/s, Ssk < 0, reflecting the micro-plowing process. For Sku > 3, all worn surfaces indicated long and narrow valleys, with high peaks, the valley are dominated as result of tearing-off glass beads and maintaining the shape of the extracted beads. Smaller values of Ssk indicate broader height distributions but these polymeric materials have narrow height distribution as all values are above 3 (**Table 2**).

Components with high volume of polymeric material are less heat conductive and prone to have melt/soften contact. The solution given by research and practice: polymeric coatings, thick enough to reduce friction and to bear wear for a specified life and reliability.

During a test, many influencing factors have to be controlled. These can be grouped in

- -mechanical and environmental test conditions (such as contact load or pressure, speed, motion type and environment temperature, composition), and
- -specimen(s) parameters (such as material composition, microstructure, volume, shape and their initial surface finish).

Some of them could be monitored during the test (as friction force), some only at before and after test. For polymers, investigations must be done just after the test as the specimens could age and thus, altering the information.

Researchers have to prioritize what factors are kept constant and what factors will vary on ranges of interest.

A full program of testing under all combinations of these factors would be time-consuming and costly, and may not be required. Often a single factor can be identified as "key" to the material response, and in this case a good approach is to set all the other factors at constant values and vary the chosen factor in a controlled way in a series of tests. Test campaign must promote an objective, to establish variables (materials, working regime parameters, environment) and the most relevant results to be given, non-destructive investigation in order to understand and direction the damage processes during testing.

Tribologists is now using mapping technique when two (or more) factors are changed in a controlled way (normally more coarsely than in parametric studies),

the parameter of interest being the friction coefficient, wear or wear rate, temperature or durability till a particular value for wear temperature etc. are reached. The mathematical model for building the map surface is very important. For instance, maps in **Figure 23** are built with double spline curves, enforcing the obtained values from the tests to be on the surface. Sharp peaks or deep zones on the maps could indicate a qualitative change in tribological processes (change in wear process balance, tribochemical reactions induced by temperature threshold etc.)

The mapping technique is efficient for determining the overall behavior of a material or a tribosystem as it provides useful data about the position of transitions in wear behavior for a systematic test campaign. This comes at the expense of a reduction in the detailed knowledge of the variation of friction and wear with any one factor, but once the regime of interest is better defined through the use of maps, then a more detailed parametric study can be conducted.

5. Characteristic mechanisms in the superficial layers of contacts implying polymeric materials

Initially, PTFE was simply used as bushes, seals, but its low mechanical characteristics make the researchers for materials to use it as matrix in composites [9, 39], adding material in other polymers, and even metallic sintered materials, more rigid and less prone to wear.

Burris and Sawyer studied the blend PEEK + PTFE [49]. PEEK has wear resistance, mechanical strength and a higher working temperature as compared to other polymers, but a high friction coefficient in dry regime μ = 0,4 and low thermal conductivity. PTFE has a high wear rate, and the fact that has the lowest friction coefficient in similar conditions does not recommend it to be used simple, without blending with another polymer or reinforcements. A qualitative model of a polymeric blend could be modeled as in **Figure 31a**.

Many researchers and producers of polymeric materials recommend only 5–20% PTFE [46, 50, 51], experiments done by Burris and Sawyer [49] obtained an optimum for the wear rate using the blend 30% PEEK +70% PTFE and, thus, underlined the necessity of testing new formulated materials for tribological applications.

Under 20% PEEK, wear has a sharp evolution, explained but not enough PEEK for creating a harder matrix for the soft polymer, thus the last one is easy to be deformed, abraded; the wear is supported by PTFE and not by the harder material (which has a higher wear resistance. The transfer process is more intense, and the wear debris have higher volumes. The authors suggest that preferentially lose of PTFE make the tribolayer grows rich in PEEK and the wear is reduced. At higher

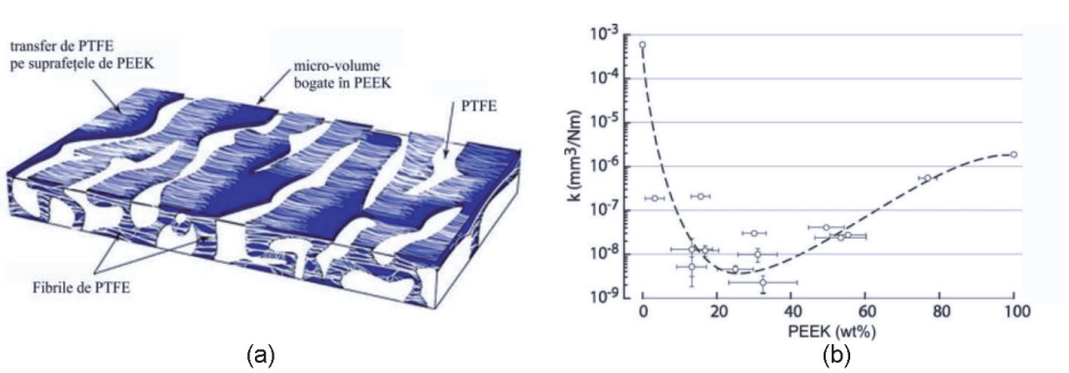


Figure 31.
Contact surface 6,35 mm x 6,35 mm, F = 250 N and alternating sliding on 25.4 mm, v = 0.05 m/s, dry sliding on stainless steel AISI 304. (a) Model proposed by [49]. (b) Wear rate as a function of PEEK concentration.

concentration of PEEK, the wear is dominated by fatigue cracks and the micro-reservoirs of PTFE are in reduced number and the solid lubrication of PTFE is done only on patches. Wear debris made of PEEK generate a more intense abrasive wear, even as third body, care damage the transfer films on both surfaces in contact.

A similar tribological behavior was noticed by Tomescu [9], when a composite copper + PTFE was tested in dry and water lubrication regime.

6. Characteristic mechanisms in the superficial layers of contacts implying polymeric materials

Neale admitted that wear is a complicated process and even if the mechanisms could be described, there are combinations and transitions among them that make them difficult to be understood yet and reduced [52]. Four main wear mechanisms are discussed in literature [23, 46]: abrasion, adhesion, fatigue and tribo-corrosion, with particular, mixt variants (thermal and tribofatigue, fretting etc.).

Aspects of wear mechanisms with different adding materials in polymers are well described and interpreted in [3, 8, 20, 46]. A particular wear process of polymeric materials is the so-called delamination, that is a combined process of sub-layer crack, plastic deformation and material removal (**Figure 32**).

Forms of abrasive wear are micro-cutting, plowing and micro-cracking with material remove are particularized for polymers that are visco-plastic materials.

Adhesion has particular aspects in tribosystems with polymers, including polymeric transfer on the counter surface, especially when this is made of steel.

As Stachowiak and Batchelor [46] mentioned, this transfer has two extreme consequences:

- beneficial, when the transfer film is thin and transform the moving contact in polymer-polymer,
- not beneficial, with lump or insular transfer, that change too much the surface topography.

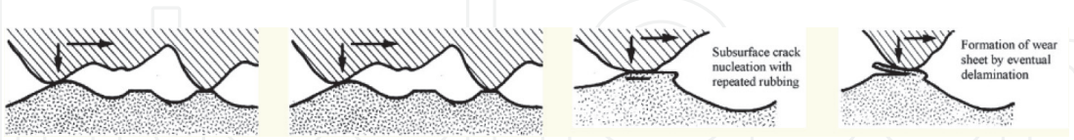
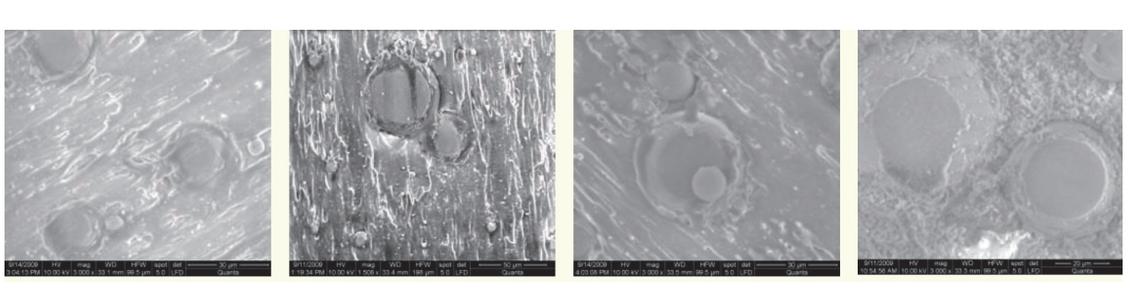


Figure 32.
Wear deterioration of a polymeric body in sliding against a harder material, also known as delamination [35].



PA+10% glass beads F = 15 N, v = 1.5 m/s | PA+20% glass beads F = 10 N, v = 1.5 m/s | PA+30% glass beads F = 15 N, v = 1.5 m/s | PA+50% glass beads F = 10 N, v = 1.5 m/s

Figure 33.
SEM images on tribolayer generated from composites with PA6 matrix and different concentrations of glass beads [11].

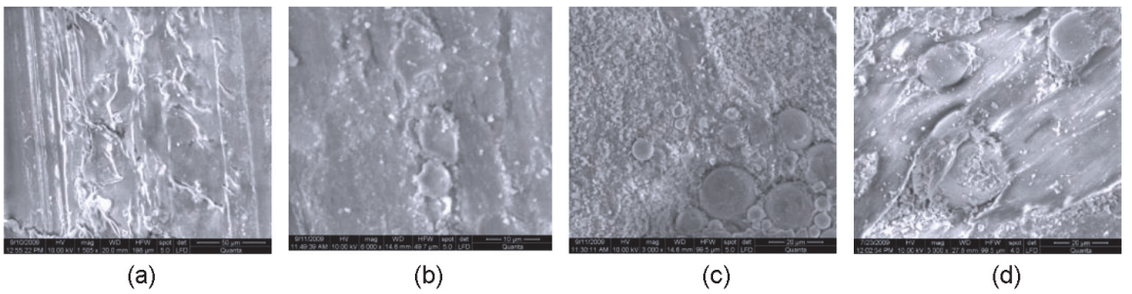


Figure 34.
SEM images for tribolayers: PA disk (a) and for the composite with 50% glass beads (b, c and d), dry sliding on steel (no gold coating of the samples) for SEM investigation. (a) v = 0.5 m/s, p = 1 MPa. (b) v = 0.5 m/s, p = 2 MPa. (c) v = 1 m/s, p = 1 MPa. (d) v = 1,5 m/s, p = 1 MPa [11].

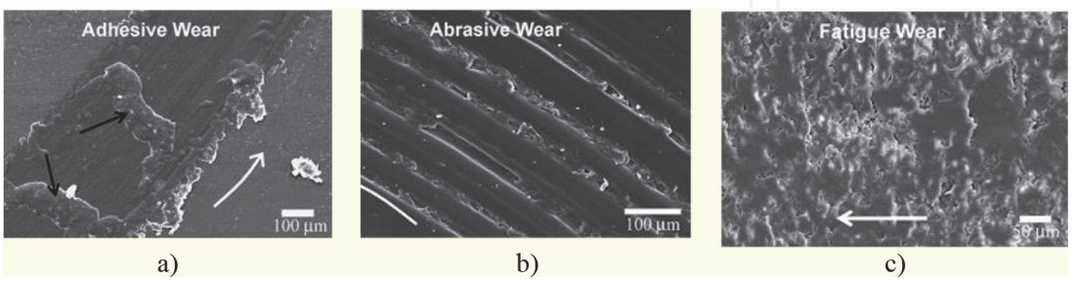


Figure 35.
Typical aspects of the failure mechanisms in sliding on steel in dry regime (a) adhesive wear, (b) abrasive wear, (c) fatigue wear [11].

The solution of reducing wear of polymers is to add materials that keep the polymer into a network (random or organized) to minimize the polymer volume implied in the local deformation and detaching small wear particles instead of big ones.

The research has to establish an optimum concentration of constituents that allow for having a better tribological behavior (reduced wear, permissible working temperature, low power loss due to friction and to keep the functions of the systems in an reliable range).

For instance, Maftei [11] elaborated composites with glass beads in a polyamide matrix with concentration between 5% wt and 50% wt and tested them on pin-on-disk tribotester. SEM investigation revealed agglomerated glass beads, a very thin soften layer of polymer that cover like a blanket the glass beads, justifying the still low friction coefficient. The next figures (**Figure 33** and **Figure 34**) point out differences between wear mechanisms for PA6 (a) (abrasive, fatigue with small cracks) and the composite (detaching smaller polymer debris, al lower sliding velocity the soften layer does not exists and polymer is deformed by the random small movements of the beads in the matrix, at higher velocity (d) several beads roll in the superficial layer as the polymer is less viscos.

Typical aspects of the failure mechanisms in polymer sliding against harder bodies are described in [53–55]: abrasive wear, adhesion wear (with transfer) and fatigue wear (**Figure 35**).

The geometry of the reinforcement makes the wear mechanism to be different for the same fibers, if the matrix is different, as one may see in **Figure 36**. The first line of SEM images is for the matrix of PA6, more ductile than PBT - the matrix of the composite in the second line of SEM images. All tests are done on block-on-ring tester, in dry regime. A more ductile matrix is easier worn and torn-off, the fibers remaining to bear the load and there visible the deformations (flows) induced by a higher load on the fiber ends. In a PBT matrix, more rigid than PA6, the transfer on the steel counterbody is less and the fibers are scratched under higher load.

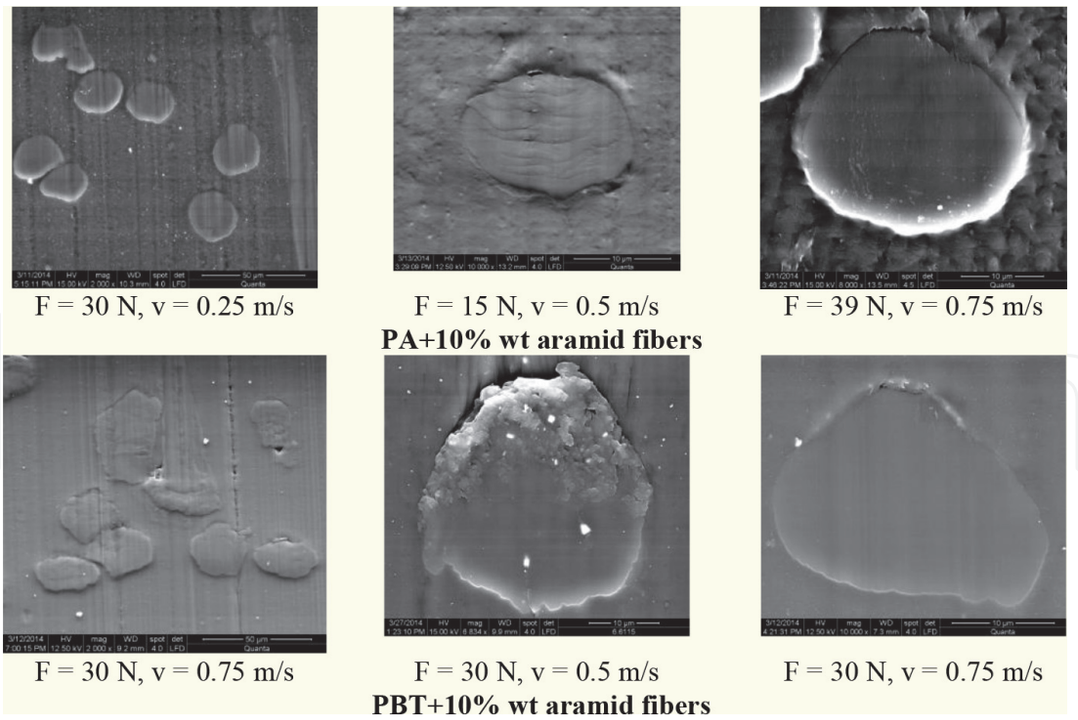


Figure 36.
Block-on-ring, L = 5000 m (thin gold coating of the samples) [16].

Composites with reinforcing particles or fibers: dynamic wear process, in stages: 1 - low wear of polymer and enrichment of the superficial layer in harder materials, 2 - too much hard particles or fibers within tribolayer, the result being big wear particles torn up in bigger conglomerate, 3 - leveling the rough surface after detaching hard particles/fibers by the help of plastic matrix (friction coefficient has high oscillations and the process is repeating.

Friction materials, as for brake pads, need special attention as they have to fulfill requirements as constant friction coefficient and controllable wear (linear would be better). Manoharan et al. [55] presented a study for a composite containing nine major ingredients, including epoxy resin, reinforcement, solid and liquid lubricants etc. (this pointing out the complexity of a composite destinated for brakes). Tests done on disk-on-plate tribotester, in the presence of third body (sand), revealed that wear volume loss of composite brake pad increases with increasing sliding distance and load, but wear rate increases with applied load and decreases with increasing sliding distance. Glass fibers and hard particle fillers were effective in reducing wear rate of the composite. It is reasonable to deduce that binders would increase the adhesion of glass fibers, SiC into the formaldehyde matrix. When the load is increased, microcracks are formed, followed by fragmentation in composite brake pad. Plowing, cracking and accelerated breakage of fibers in composite are evident under higher load. This study is here given in order to underline the necessity of testing new formulated friction materials, no theoretical model being able to reliably predict the tribological behavior in terms of values for wear, friction and durability.

Samyn et al. [56] presented a useful review on tribology of polyimides. Temperature modifies the tribological behavior of this polymer by chemical effects.

The tested sintered polyimides show two sliding regimes: between 100°C and 180°C, friction is high and wear rate increases, with a discontinuous minimum at 140°C. Raman spectroscopy motivated that hydration generates a reversion of polyimide into a precursor. A maximum hydrolysis intensity at 140°C explains the minimum wear rate with acid groups acting as a lubricant. From 180–260°C, friction decreases and wear rate become stable at mild loads, with a maximum value for

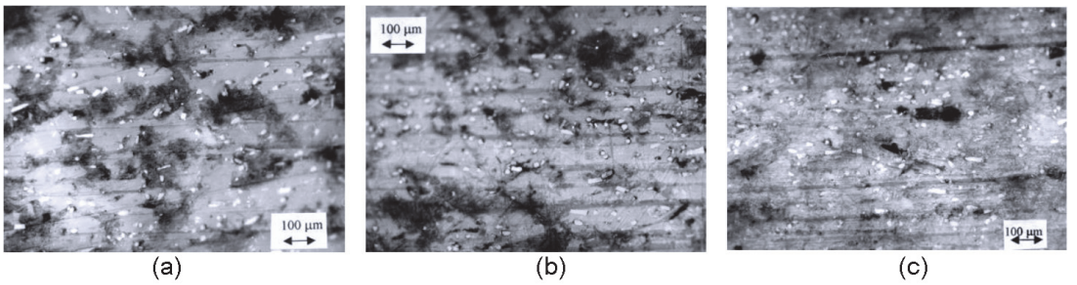


Figure 37.
Images of the partial bearings made of PTFE + short glass fibers with different concentrations, test conditions: v = 2.5 m/s and p = 4.6 MPa, water lubrication, L_x = 10,500 m [8]. (a) 15% glass fibers. (b) 25% glass fibers. (c) 40% glass fibers.

the wear rate at 180°C. Wear rates increase at high loads, but brittleness is not obvious till 150 N, at high temperatures. A discontinuous platelet transfer film develops above 180°C.

Thermoplastic polyimides show three sliding regimes that are related to a combination of chemical and thermal effects.

- at 100 to 120°C, friction increases and is higher and wear rates are lower as compared to sintered polyimides; a thin transfer film develops; dark wear particles were produced by hydrolysis,

- at 120 to 180°C, friction decreases and a transition to high wear rates is initiated; a patchy-like transfer film develops and the polymer surface becomes irregular and opaque due to softening and chemical modification; wear debris become brittle and act as an abrasive,

- at 180–260°C, friction increases and overload wear results from melting; a thick transfer film develops, and the polymer surface smoothens. Roll-like debris are visually observed as an indication for melting. Raman investigation indicates thermal decomposition of aromatic structures into amide monomers on the polyimide surface, weakening strength and producing higher wear.

And study point out the importance of test parameters, here the two polymers, the temperature and the load. Such a study could be done for each polymer of interest, with particular values for the test parameters, as they do not have a pattern due to their diversity in chemical structures and molecular organization.

Agglomeration of reinforcement fibers of particles are observed even in lubricated system with polymer composites sliding against steel. A suggestive model of reinforcements agglomeration in the superficial layer of polymeric composites, due to preferential wear of the polymer matrix has been described by Blanchet and Kennedy [10] from 1992, and then developed by Han and Blanchet in 1997 [57] and experimental results given in **Figure 37** sustained their model. Each worn surface after sliding in water has a similar concentration in short glass fibers, even if initially the concentrations were different.

7. Tendency in using polymeric materials and conclusions

New development in processing polymer-based materials (here including polymers, polymer blends, polymer composites and stratified materials based on polymeric fabrics) make easier to replace metallic parts with ones made of polymer-based materials, at a convenient price.

Test campaign are running faster as the market obliged the designers and producers to give more reliable products and the new achievement in monitoring and investigating the tribological behavior help them to understand and formulate new and adequate materials.

An obvious tendency for these materials is using them as coating, thick enough to fulfill an imposed reliability and durability.

New technologies allow for a better dispersion of the constituents, making the resulting materials more predictable [58–60].

8. Conclusion

Testing is very important when using polymer-based materials. New recipes of polymer-based materials has to follow the logical chain of testing, meaning laboratory specimen - component - partial system - entire system, in order to avoid catastrophic failure of the entire system. Even if it is difficult to imagine now new tribological parameters to be monitored or calculated, variant versions could be adapted for particular applications.

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