Polymer Tribology: Current State and Applications

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A B S T R A C T

Polymer tribology is based on the analysis of abrasion, adhesion, and fatigue of polymer materials in a friction contact. The structural features of polymers provide a variety of tribological applications of basic polymers mostly as matrices and fillers of composite materials. Recently polymer nanocomposites are used for making components of various tribosystems. A short review of polymer materials for tribosystems is presented. The main results of studies in friction and wear of polymers are given. Formation of the real area of contact is evaluated when taking account of polymer viscoelasticity and the effects of temperature and load in the contact. Adhesion of polymers and its part in friction transfer is considered. Various aspects of friction and wear tests of polymer materials for estimation of their characteristics, prediction of service life in different operational conditions are discussed. Practical examples of applications of polymer composites and nanocomposites in various branches of industry are given.

1. INTRODUCTION

Polymer tribology considers the regularities of friction and wear of polymers and polymer-based composites. The basics of polymer tribology suppose that there are two components of friction – adhesion and deformation, although the interrelation of these components is complicated [1,2].

The adhesion component is attributed to interfacial bonds formed on the contact spots and it is dependent on surface forces. The deformation component results from the resistance of polymer to deformation and it is strongly dependent on depending on the material properties. Wear of polymers is strongly dependent on combination of friction parameters, mechanical properties of polymer, and transformation of polymer under these factors. The flexibility in changing the polymer properties in blending and combination with various fillers gives a variety of tribological applications. Polymer nanocomposites promise more wide choice of applications. Tribotesting of polymers needs the discussion on the proper selection of its conditions and data presentation.

2. EFFECT OF EXTERNAL FACTORS ON FRICTION OF POLYMERS

2.1 Effect of load

It is supposed that the friction force is proportional to the normal load; and

experiments have shown this law to be valid for some polymers at mild and severe contact pressure (PTFE, PMMA, PVC, PE, and PA). It seems natural for plastic deformation in the contact. At low contact pressure the friction coefficient decreases with increasing the load due to elastic deformation of polymer. So, the friction coefficient dependence on load passes the minimum which corresponds to transition from elastic contact to plastic one [2].

2.2 Effect of sliding velocity

At low velocities the viscous resistance of polymer in the contact zone grows with increasing velocity. At high velocities the polymer in the contact zone demonstrates elastic behaviour; as a result, the friction force depends slightly on velocity or decreases with velocity increase. In the intermediate velocity range all the above factors are in competition that results in the maximum on the friction force-sliding velocity curve; the position of the maximum depends on the relaxation characteristics of the polymer [3].

2.3 Effect of temperature

Polymers are very sensitive to frictional heating and friction is a typical dissipative transformation of mechanical energy into heat.

Hence, adhesion is considered as the basic mechanism of polymer friction in the highly-elastic state over the smooth surfaces. When polymer is in the glassy state mechanical losses are dependent more on deformation. As the polymer is heated, the contribution of the mechanical component of the friction force increases and at glass-transition it becomes comparable to the contribution of the adhesion.

3. WEAR OF POLYMERS

The wear of polymer-based materials is caused by variety of physical and chemical processes. Yet, abrasion, adhesion, and fatigue are generally recognized as the basic modes.

Abrasive wear is caused by hard asperities on the counterface or hard particles that move over the polymer surface.

The adhesive mode of wear occurs in the sliding of polymer over unlike surface, when the strength of the adhesive bonds in the contact exceeds the cohesive strength of the polymer. As a result, some part of the material is transferred onto the counterface as a film; another part is removed as debris.

The fatigue wear of polymers is considered as an accumulation of damage at cyclic stresses in material surface layer at sliding.

3.1 Abrasive wear

Abrasion appears as scratches, gouges, and scoring marks on the worn surface; the debris are frequently shaped as chips (Fig. 1).
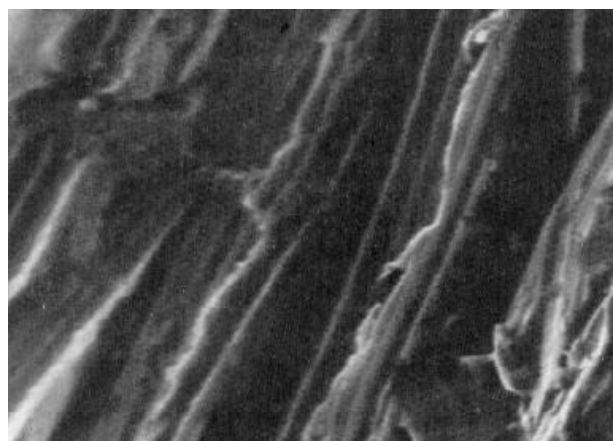

Fig. 1. Typical image of signs of abrasive wear.

It was shown experimentally that the abrasive wear rate is proportional to the ultimate tensile stress of material and the corresponding strain [1,4].

3.2 Adhesive wear and friction transfer

This wear mode involves the formation of junctions due to adhesion of polymer to counterface followed by junction growth and rupture. As a result, a film of the transferred polymer appears on the counterface.

The kinetics of friction transfer governs much the wear rate of polymers [1,5]. If polymer particles of micrometer size are transferred from one surface to another the wear rate varies slightly. Under certain conditions the polymer is transferred to the counterface as a thin film which is continuously carried away from it; in this case the wear rate increases.

For example in case of PTFE it is transferred as flake-like particles of very small size. The thickness of the transfer film increases monotonically and then oscillates about a mean value; the magnitude and amplitude of the oscillations are governed by the test conditions [5,6].

Transferred polymer fragments may show a variety of shapes depending on polymer properties and operating conditions (Fig. 2). Sometimes they can be even formed as melted spheres (Fig. 2e) but mostly as fragments of films with various thicknesses.
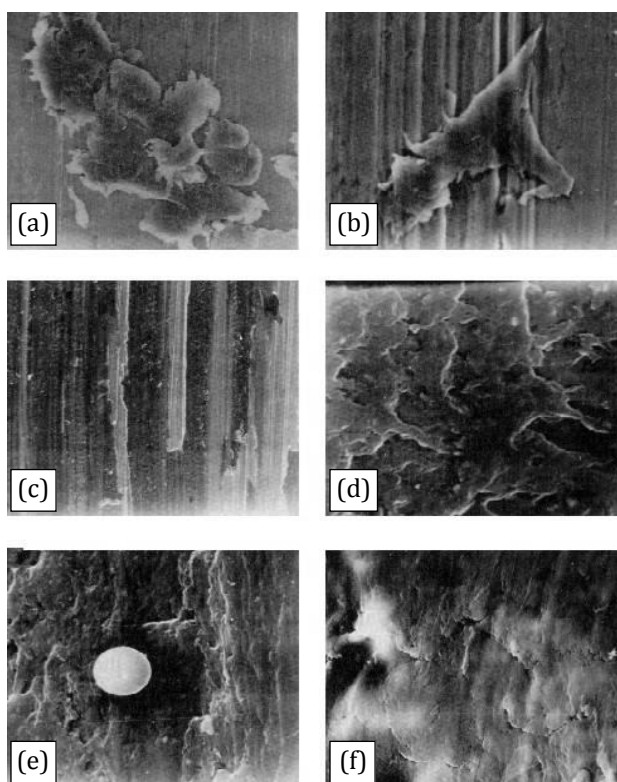

Fig. 2. Polymer transfer fragments at friction against steel: (a) and (b) HDPE, (c), (d) and (e) PA and (f) PTFE.

3.3 Fatigue of polymers

The formation of wear debris at polymer fatigue is a multi-stage wear process. As friction contact occurs on asperities of the rubbing surfaces, the area of real contact spots is a small part of the contact. Therefore, even under light loads the pressure on these spots is capable of inducing their plastic deformation and pulse heating. Repeated heating and deformations of polymer favour the nucleation of defects in its surface layer. As friction continues, new defects appear and accumulate, merge into pores and cracks, then debris leaves the friction zone (Fig. 3).
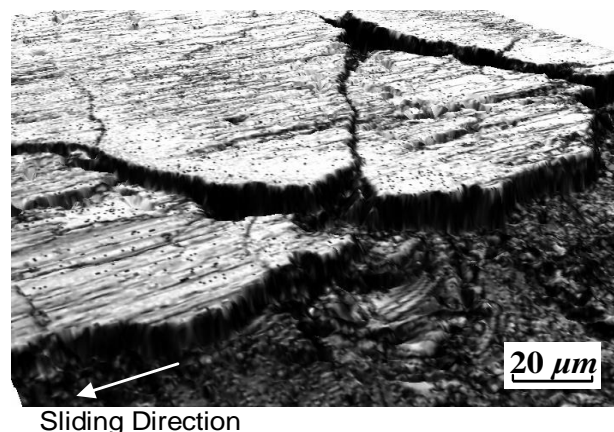

Sliding Direction

Fig. 3. Fatigue wear of phenol formaldehyde resin.

The fatigue wear rate of polymers correlates with their strength characteristics. Increase of the ultimate strength of polymer improves its fatigue resistance. One of the ways to improve the fatigue resistance of polymer is to reduce its friction coefficient, e.g. by introducing the antifriction filler [7].

4. TRIBOLOGICAL APPLICATION OF POLYMERS AND POLYMER COMPOSITES

Such properties of polymers, as chemical inertness, self-lubricating behaviour, and low wear rate at dry friction, have made them promising for tribological applications [1,8]. Polymers may be divided into the following three groups: thermoplastic polymers, thermosetting ones, and elastomers. The overview of various polymers used in tribology and their properties are given in the Table 1.

Thermoplastic polymer-based materials have gained acceptance mainly for their self-lubricating properties. The most illustrative example of such materials is PTFE. Under heavy loads and at low sliding velocities the friction coefficient of PTFE in pair with metals is very low; it is close to that of lubricated metals. This makes PTFE the excellent material for sliding bearings even pure PTFE has low yield strength. Antifriction PTFE-based materials contain various fillers improving the strength properties of the matrix polymer (coke, soot, fibres, metal powders, graphite, molybdenum disulphide etc).

Table 1. Tribological characteristics of polymers.

Material	Friction coefficient	Operation temperature [°C]	Advantages	Disadvantages
Aliphatic polyamides	0.2 ÷ 0.5	– 40 ÷ + 85	Low wear and high fatigue resistance	Water sorption, high coefficient of friction
Aromatic polyamides	0.1 ÷ 0.3	– 100 ÷ + 200	Low wear, high fatigue resistance and heat stability	High cost, water sorption
Fluoroplastics	0.01 ÷ 0.05	– 269 ÷ + 260	Low friction, resistance to aggressive media	Creep and low mechanical strength
Polycarbonate	0.2 ÷ 0.5	– 60 ÷ + 125	Rigidity and resistance to aggressive media	Low fatigue strength
Polyacetals	0.1 ÷ 0.3	– 50 ÷ + 120	High wear and fatigue resistance	Abrasive effect due to high rigidity
Polyolefins	0.1 ÷ 0.3	– 100 ÷ + 100	High resistance to aggressive media	Low mechanical strength
Polyalkylene terephthalate	0.1 ÷ 0.3	– 20 ÷ + 115	Resistance to aggressive media and heat resistance	Sensitivity to hot water
Thermoplastic elastomers	0.3 ÷ 0.6	– 60 ÷ + 120	High elasticity and resistance to ambience	High friction and low mechanical strength
Polyetherether ketone	0.2 ÷ 0.4	– 30 ÷ + 250	High heat and ambient resistance, and γ-radiation.	High cost
Polyphenylene sulfide	0.2 ÷ 0.5	– 30 ÷ + 220	High wear and fatigue resistance	High cost

PTFE is also applied as antifriction filler for thermoplastic and thermosetting polymers. Other applications are linings consisting of a metal substrate (steel) and an upper porous layer (bronze) impregnated with PTFE-based composition. Bearings with such materials are most efficient under heavy pressure and at low sliding velocity without lubrication.

Polyamides are used to fabricate sliding bearings with reinforcing fillers and dry lubricants. They are also good for polymer gears and thin polymer coatings.

Polyolefins are widely used as a matrix for antifriction composites and additives to other polymers, even their disadvantage is low thermal resistance.

Polymer gears, bushings, and sliding bearings are also made of polyformaldehyde, polycarbonate, and polyarylates.

Among the thermosetting polymers used for antifriction applications are polyimides which have a high operating temperature (up to 220 – 260 °C).

Epoxy and phenol resins are applied as matrices for antifriction composites filled with solid lubricants like graphite or molybdenum disulfide, so they are often used in linings of machine guides [7]. Thermosetting polymers also serve as matrices of materials for brakes, clutches, and other frictional units.

Elastomers such as rubbers and polyurethanes are often used as antiabrasion linings of metal surfaces and contact seals. But the most important applications of elastomers are automotive tires [4].

5. POLYMER NANOCOMPOSITES

Polymer nanocomposites are typically formed while filling the polymer by particles or fibbers. Carbon nanofillers are very attractive for such purpose. Homogenious distribution of nanotubes and fullerenes can be achieved in extrusion of polymers with high shear rates.

Polymer composites with metal nanofillers can be formed by introduction of particles into the melt matrix of by mixing them with the polymer powder and further melting and pressing. Another way is the using of decomposition of metal compounds in polymer melt. The price of carbon nanofillers is a limiting factor in their applications for polymer composites. Other promising choices as polymer nanolayers have an application area in MEMS and NEMS systems

where the price of nanopolymer is not a limiting factor [9].

Polymer-clay nanocomposites are very prospective due to their low price and availability of mass-production [10]. But the laminated silicates used as nanofillers need usually increasing compatibility with the polymer matrix, so their surface should be modified by surface-active agents. Chemosorption of them reduces the surface energy of filler and increases the wettability. Figure 4 illustrates the scheme of forming polymer-clay composite and their properties are given in the Table 2.
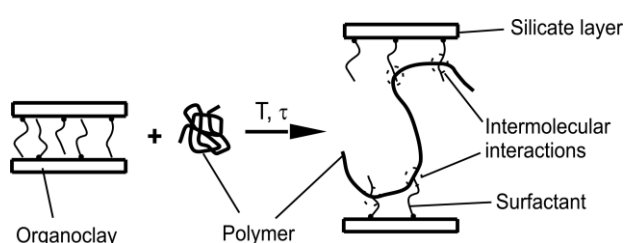

Fig. 4. Scheme of polymer-clay composite formation.

Table 2. Properties of polymer-clay composites.

Composition [wt. %]	Mode of processing	σ_T [MPa]	ε [%]	$I_{abr.} \times 10^3$ [g/m]
PA 6 / nanoclay (MMT) – 3 %	in melt	75	76	2.8
PA 6 /nanoclay (MMT+ODA) – 3 %	in melt	86	53	4.0

Abrasive wear test conditions: p = 2 MPa, v = 0.35 m/s; pin-on-ring, counterface: abrasive paper.

6. TRIBOTESTING OF POLYMERS

Due to complexity of designing the proper material for particular applications, practical tribology is based on testing the materials under conditions close to real operation in a wide range of operation parameters and environments [11]. Most of the methods in tribotesting of materials can be applied to polymers, but such testing needs to take account of rheology, visco-elasticity and thermal behaviour of polymers.

Nowadays it is common to define the working area of polymers limited by their operation temperature and pressure-velocity limit related to certain wear rate.

Pressure-velocity (*PV*) factor is a complex characteristic of mechanical, velocity, and thermal effects, so in SI units it follows:

$$PV = \left[\frac{N}{m^2} \frac{m}{s} \right] = \left[\frac{J}{m^2 s} \right] = \left[\frac{W}{m^2} \right]. \qquad (1)$$

Basically, *PV* defines the power [W] applied to the friction contact area. It is possible to estimate the contact temperature based on *PV* factor while using the friction coefficient as:

$$T = T_0 + CfPV, \qquad (2)$$

where T_0 is an ambient temperature and C is a coefficient of heat transfer in a tribosystem.

On the other side, wear *I* is also dependent on *PV*

$$I = kPV, \qquad (3)$$

where k is a coefficient, dependent on material properties.

Pressure-velocity factor characterizes both the area of contact, load, and velocity, as well as power transfer in the tribosystem, so if taking in mind the heating role it looks the most important for characterization of polymers in tribotests.

Estimation of the tribological performance of polymer materials can be a definition of the approved area on the *PV* map. Such an area can provide the safe and long-life operation of the tribosystem with the approved wear rate typically equal 0.25 mm/hour.

The tribotests can be done with the common scheme of the block-on-ring contact. Steel ring with 40 mm outer diameter and thickness of 12 mm (medium-carbon steel 45, HRC 45 – 50, *Ra* = 0.32 μm) is used as counter-body for polymer block [12].

The tests can be done at different combinations of load and velocity, but the temperature in the contact is considered as an additional parameter. It is possible to obtain an area of the efficient operation at the map of *PV*. The line of the approved wear rate is fixed on this plane, then the map of polymer behaviour is plotted (Fig. 5).

We have emphasized the effect of heating in tribology of polymers. For example, the

mechanical properties of thermoplastics are dramatically affected by temperature. So, if we need to provide the stable friction at given scale of load-velocity, we need to find the correlation of the *PV* factor and the effective range of friction coefficient. Such a correlation is presented in Fig. 6.
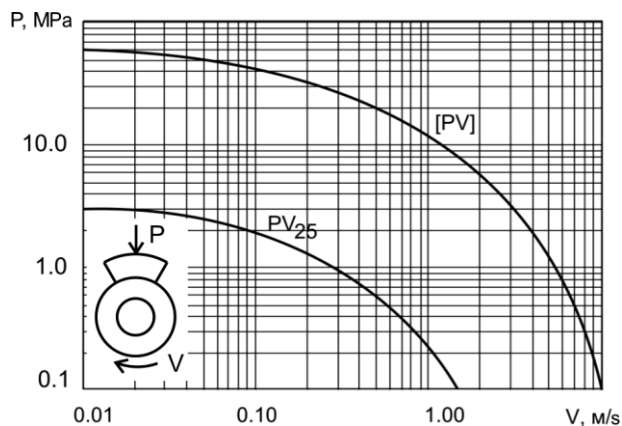

Fig. 5. *PV* map of PA-6 rubbed against the medium-carbon steel.
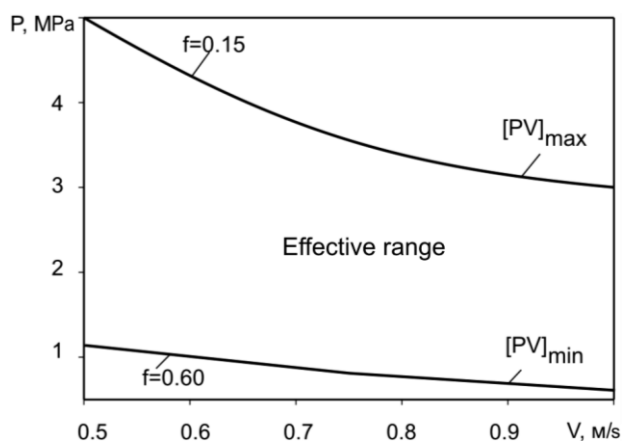

Fig. 6. The range of *PV* limited by minimal and maximal values of the friction coefficient.

Still, the method proposed here is not standardized yet, but it can be efficiently used in the short-term evaluation of the comparative tribological performance of the polymers.

7. CONCLUSIONS

The main concept of polymer tribology is based on understanding the effects of surface adhesion, shear and deformation of rubbing materials resulting in the real area of contact of rough surfaces.

Polymer tribology has grown quickly following the wide application of polymer-based materials in engineering due to the use of different fillers greatly improving the tribological behaviour of neat polymers.

Accumulation of research data on structure, chemical and mechanical properties of polymers and polymer composites has laid a solid basis for improving efficiency of polymer tribosystems.

Polymers with nanofillers that are produced at commercial scale are taking over the areas traditionally occupied by other materials.

Methodology of testing the polymers is developing with taking account of the important part of heating in their tribological performance.

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