Polymer mechanics and tribology

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Abstract

Purpose – The purpose of this paper is to review the advances in mechanics and tribology of polymers and polymer-based materials. It is focused on the understanding of the correlation of contact mechanics and the tribological behavior of polymers and polymer composites by taking account of surface forces and adhesion in the contact.

Design/methodology/approach – Mechanical behavior of polymers is considered a viscoelasticity. Tribological performance is estimated while considering the parts of deformation and adhesion in friction arising in the contact. Surface energy, roughness, load and temperature effects on the tribological behavior of polymers are evaluated. Polymer composites produced by reinforcing and by the addition of functional additives are considered as materials for various applications in tribology. Particular attention is given to polymer-based nanocomposites.

Findings – A review of studies in tribology has shown that polymer-based materials can be most successfully used as self-lubricating components of sliding bearings. The use of the fillers provides changes in the tribological performance of neat polymers and widens their areas of application in the industry. Thin polymer films were found to be prospective lubricants for memory storage devices, micro-electro-mechanical systems and precision mechanisms. Further progress in polymer tribology should be achieved on solving the problems of contact mechanics, surface physics and tribochemistry by taking account of the scale factor.

Originality/value – The review is based on the experience of the authors in polymer mechanics and tribology, their research data and on data of many other literature sources published in this area. It can be useful for specialists in polymer research and industrial engineers working in tribology and industrial lubrication.

Keywords Polymers, Wear, Friction, Mechanical properties, Adhesion

Paper type General review

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A, A_{vis}, A_{app}, A_{rea}$</td>
<td>contact area, contact area in viscoelastic case, apparent contact area, real contact area, contact radius</td>
</tr>
<tr>
<td>$E, E', E^*$</td>
<td>elastic modulus, combined elastic modulus, effective elastic modulus</td>
</tr>
<tr>
<td>$F, F_{pull-off}, F_{at}, F_{elas}$</td>
<td>normal load, pull-off force, elastic force, attraction force</td>
</tr>
<tr>
<td>$G, G_r$</td>
<td>shear modulus, relaxation modulus</td>
</tr>
<tr>
<td>$h, h_0$</td>
<td>distance, equilibrium distance</td>
</tr>
<tr>
<td>$K$</td>
<td>bulk elastic modulus</td>
</tr>
<tr>
<td>$p(x', y')$</td>
<td>normal pressure at point $(x', y')$</td>
</tr>
<tr>
<td>$R, R_a$</td>
<td>ball radius, average roughness</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>rheological parameter</td>
</tr>
<tr>
<td>$\beta$</td>
<td>asperity radius</td>
</tr>
<tr>
<td>$\Delta_{Tob}, \delta$</td>
<td>Tabor parameter, deformation (displacement)</td>
</tr>
<tr>
<td>$\sigma, \sigma_r, \sigma_s$</td>
<td>strain, strain tensor, root mean square of height</td>
</tr>
<tr>
<td>$\eta_\alpha$</td>
<td>viscosity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>distance from point $(x, y)$ to point $(x', y')$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>relaxation time</td>
</tr>
</tbody>
</table>

$\gamma, \gamma_1, \gamma_2, \gamma_{12}$ = work of adhesion, surface energy of surface 1, surface energy of surface 2, interfacial energy

$\lambda$ = phenomenological parameter of relaxation

$\nu$ = Poisson’s ratio

$\sigma, \sigma_r, \sigma_s$ = strain, strain tensor, root mean square of height

$\eta_\alpha$ = viscosity

$\rho$ = distance from point $(x, y)$ to point $(x', y')$

$\tau$ = relaxation time

1. Introduction

The mechanical behavior of polymers is governed by the combination of elasticity and viscosity (Myshkin and Kovalev, 2009; Myshkin and Petrokovets, 2004). The mechanical properties of polymers can be greatly affected by blending with other polymers and by filling with materials of different origin (metals, ceramics and polymers) in the form of fibers or powders over a wide range of sizes and shapes (Pesetskii and Bogdanovich, 2013).

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For tribological applications, the most important aspect of polymer mechanics is the contact interaction with the surfaces of solids in relative motion. In such an interaction, the contact adhesion and deformation are the key factors that are greatly affected by surface roughness, hardness and surface energy of the contacting bodies. Polymer surface asperities experience elastic, plastic and visco-elastic deformation depending on the material properties (Kovalev and Myshkin, 2013; Myshkin et al., 2014, 2005, 2015). The deformation component of friction results from the resistance of the polymer to "ploughing" by the asperities of the harder counterface. The adhesion component stems from the adhesive junctions formed on the spots of real contact between the mated surfaces. In general, the adhesion component of friction for polymers is believed to exceed by far the deformation.

It is known linear macromolecules of polymers are large in size, and the main feature of the polymer structure is that macromolecules consist of the rigid segments which can rotate, thus providing the flexibility of the molecular chains. Another feature of the polymers is that strong chemical forces link the atoms in a polymer chain, whereas the intermolecular forces, which are significantly weaker, link the chains. The structural features of polymers provide a complicated mechanical behavior of polymers and polymer composites (Satyanarayana et al., 2007; Sinha and Briscoe, 2006). Contact load, velocity and temperature are the other important factors affecting the mechanical performance of polymers and polymer composites at friction (Shull, 2002). These factors determine the formation of the real contact area, coefficient of friction and wear of the contacting bodies (Bowden and Tabor, 1964; Ludema and Tabor, 1966).

Low mass density of polymers and the possibility of changing their properties within a wide range provide a variety of their applications in tribology. The purpose of this paper is to summarize our current theoretical and experimental understanding of polymer mechanics, as it applies to a variety of tribological problems in modern polymer science.

2. Mechanical behavior of polymers

2.1 Contact mechanics

The common assumption of contact mechanics is that the two surfaces in contact are frictionless, so that interfacial stresses cannot be strengthened at the interface. Considering the contact mechanics, we need to estimate the contact area which depends on roughness, properties of materials and variations of these properties at frictional heating. The contact area is determined based on theory of viscoelasticity.

The contact problem on penetration of rigid ball into elastic half-space is found from the integral equation presented in Hertz classical theory of contact:

\[
\frac{1}{\pi} \int_{A} E \frac{p(x', y')}{\rho} dA = \delta - l_1 x^2 - l_2 y^2
\]  

(1)

where \( E = \frac{K - G}{2} \); \( \rho = \left( (x-x')^2 + (y-y')^2 \right)^{1/2} \); \( K \) and \( G \) are bulk and shear moduli, respectively; \( A \) is the contact area; and \( l_1 \) and \( l_2 \) are constants of major and minor ellipses’ axes, respectively.

The viscoelastic mechanics treatment that has been described here is based on an exponential dependence of the deformed volume and the viscosity creep that is expended in the compressed region. When this compressed region is small, the overall relationship between \( a, F \) and \( E^* \) is still accurately described by an elastic analysis, even though viscoelastic effects may be important in the large compressed region. In this case, specification of the relationship between \( E^* \) and \( t \) (by specification of the phenomenological parameter \( \lambda \)) and of the elastic modulus of the compliant material are all that is necessary to determine the relationship between load \( F \) and displacement \( \delta \) for a specified experimental geometry.

2.2 Viscoelastic properties

The results presented in the previous section assume that the contacting materials have well-defined elastic constants. In fact, the mechanical behavior of polymers is governed by the combination of elasticity and viscosity. At small deformations, polymers behave as the elastic body (\( \sigma = E \varepsilon \), where \( \sigma \) and \( \varepsilon \) are the stress and strain and \( E \) is the modulus of elasticity) modeled with a spring and Newtonian fluid (\( \sigma = \eta \varepsilon / \partial t \), where \( \eta \) is the viscosity and \( t \) is the time); the latter is presented by a damper.
2.3 Contact problems with adhesion

The adhesion between two surfaces may be because of the chemical or physical interactions at the areas where the materials are in intimate contact. In the contact of polymer surfaces, the adhesion is mainly due to the formation of rather weak vander Waals bonds and also hydrogen bonds. They involve surface atoms that have free unsaturated bonds or dipole–dipole interactions between polar molecules.

The thermodynamic concept of the work of adhesion per unit area has been usually indicated with $\gamma$ and represents the energy that must be theoretically supplied to separate two surfaces in contact. The work of adhesion between Solids 1 and 2 is determined by the Dupre formula $\gamma = \gamma_1 + \gamma_2 - \gamma_{12}$, where $\gamma_1$ and $\gamma_2$ are the surface energies required to form the unit surfaces of Solids 1 and 2 (their free surface energy) and $\gamma_{12}$ is the excess surface or interfacial energy. It should be noted here that the Dupre formula is valid for a contact of the liquid and solid surface. The direct application to the contact of two solids is an assumption only. For a proper value of work of adhesion, the direct measurements should be used (Borodich et al., 2013).

Two basic models have been developed to describe the contact adhesion: the Johnson–Kendall–Roberts (JKR) model (Johnson et al., 1971) and the Derjaguin–Muller–Toporov (DMT) model (Derjaguin et al., 1975).

The JKR model is based on the assumption that interactions occur only within the contact area. Elastic contact between a sphere of radius $R$ and half-space is affected by vander Waals forces in addition to the applied load. The formula for calculating the radius of JKR’s adhesive contact is:

$$a^3 = \frac{3}{4E^*} \left( F + 3 \pi R \gamma + \sqrt{6 \pi RF \gamma + (3 \pi R \gamma)^2} \right)$$

Where, $F$ is the normal load.

Without adhesion ($\gamma = 0$), the Hertz equation is obtained, while if $\gamma > 0$, the contact area exceeds the Hertzian contact area at the same load $F$.

The application of a tensile load can reduce this radius, and then the contacting surfaces would separate at the least load corresponding to the conversion of the radicand into zero:

$$F_{\text{pull-off}} = -\frac{3}{2} \pi R \gamma$$

Nowadays, the classical frictionless JKR model in the range of its applicability has been generalized to the adhesive contact problem for an arbitrary convex, blunt axisymmetric indenter, transversely isotropic and prestressed materials, in particular to the case of the punch shape being described by monomial punches of an arbitrary degree (Borodich, 2014; Borodich et al., 2014b).

The DMT model is based on the following two postulates: surface forces do not change the deformed profile of the sphere and it remains Hertzian. The attraction force acts outside the contact pressing the bodies together with the contact region being under compression by the stresses distributed according to Hertz.

Equilibrium is reached when the deformation is sufficient for the elastic response $F_e$ to counterbalance the joint effect of the load $F$ and the forces of attraction $F_c$:

$$F_e = F + F_c$$

In this case, the attraction is represented by the Lennard–Jones potential, and the attraction force is calculated by integration:

$$F_c = 2 \pi \int_a^\infty r\delta(h + h_0)rdr$$

Where, $h_0$ is the clearance within the contact site.

There are approximate formulas which facilitate the use of the DMT model. In particular, there is a simple relation between the load and contact radius:

$$a^3 = \frac{3}{4E^*} \left( F + 2 \pi \Delta \gamma R \right)$$

The force of separation in this case is $F_s = -2 \pi \Delta \gamma R$.

Each of two models is correct for the certain physical–mechanical combinations and roughness of the bodies (Figure 1).

The DMT theory is applicable to materials for which the point with the coordinates $(E^*, \gamma)$ lies below the corresponding line plotted at the constant radius of asperity $\beta$. Here $E^*$ is the effective elastic modulus of the contacting materials and $\gamma$ is the interface energy.
introduced into equation (15) in addition to roughness parameter, the condition ΔC < 0.1 can occur only in the case when at least one of the contacting bodies is completely elastic. Theoretical and experimental studies have shown that contact is formed by adhesion and surface forces are dominant when ΔC > 0.1. Since physical—mechanical properties of mating materials are introduced into equation (15) in addition to roughness parameter, the condition ΔC ≥ 0.1 can determine the ultimate mean arithmetic deviations of the equivalent roughness Ra = (Ra1 + Ra2)1/2 below which the adhesion in the contact should be taken into account (Figure 2).

The analysis indicates that it is impossible to study the contact of polymers at unless the atomic and molecular interactions between the surfaces are taken into account (Myshkin et al., 2001).

2.4 Contact of rough polymer surfaces

The relationship between the load F, contact radius a and approach of the sphere δ is sought as a superposition of the solutions considering mechanical loading and heating. It is possible to find the real area of all contact spots (RCA) following the Greenwood–Williamson model (Greenwood and Williamson, 1966). The non-dimensional equations for the normal distribution of the asperity heights are written as follows:

\[
\frac{A_r}{A_d} = \pi RD\sigma_r \frac{1}{\sqrt{2\pi}} \int_{h}^{\infty} (\xi - h) \exp \left[ -\xi^2/2 \right] d\xi 
\]

(16)

\[
\frac{F}{A_d} = \frac{4}{3} \frac{\sqrt{1/\pi}}{R} D\sigma_r \frac{1}{\sqrt{2\pi}} \int_{h}^{\infty} (\xi - h)^{3/2} \exp \left[ -\xi^2/2 \right] d\xi 
\]

\[+ \frac{2\alpha T}{\pi} (1 + v) RD\sigma_r \frac{1}{\sqrt{2\pi}} \int_{h}^{\infty} (\xi - h) \times \exp \left[ -\xi^2/2 \right] d\xi
\]

(17)

here \(A_d\) is the apparent contact area, \(A_r\) is the real contact area, \(D\) is the surface density of asperities, \(\sigma_r\) is the root mean square roughness, \(\alpha\) is the bandwidth parameter, \(\xi\) is the non-dimensional height of asperity and \(h\) is the non-dimensional separation.

The RCA of the bodies becomes smaller when the temperature difference of bodies increases, but this RCA decrease may be balanced by its rise due to the softening of the material.

Using the following relations, \(\tilde{A} = A_r/A_d\); \(\tilde{W} = \frac{\tilde{W}}{A_d (1-\nu^2)}\); \(\tilde{D} = RD\sigma_r\); \(\tilde{\sigma} = \sigma/R\) and designations \(F_1(h) = \frac{1}{\sqrt{2\pi}} \int_{h}^{\infty} (\xi - h) \exp \left[ -\xi^2/2 \right] d\xi\), \(F_{3/2}(h) = \frac{1}{\sqrt{2\pi}} \int_{h}^{\infty} (\xi - h)^{3/2} \exp \left[ -\xi^2/2 \right] d\xi\), equations (16) and (17) are rewritten as:

\[
\tilde{A} = \pi \tilde{D} F_1(h)
\]

(18)

\[
\tilde{W} = \frac{4}{3} \tilde{D} \sqrt{\tilde{\sigma}} \left[ F_{3/2}(h) + \frac{3}{2\pi} \frac{\alpha T}{\sqrt{\tilde{\sigma}}} (1 + v) F_1(h) \right]
\]

(19)

These equations describe the dependence of the relative RCA on load in the parametric form, while the separation \(h\) is used as the parameter. For isothermal contact, equation (19) follows:

\[
\tilde{W}_H = \frac{4}{3} \tilde{D} \sqrt{\tilde{\sigma}} F_{3/2}(h)
\]

(20)

If the rheological behavior is governed by a single relaxation time, the simple exponential dependence describes its temperature-dependent modulus:
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\[ E = E_0 \exp[-\alpha T] \]  

(21)

where \( \alpha \) is a constant having dimension of the reciprocal of the temperature and conventionally termed as the rheological parameter. Substituting equation (21) in equation (19), we get a parametric system of equations, describing the temperature dependence of the RCA. This system involves equation (21) and modified equation (19) in the form:

\[ W_0 \exp(\alpha T) = \frac{4}{3} D \sqrt{\alpha} \left[ F_{3/2}(h) + \frac{3}{2 \pi \sqrt{\alpha}} (1 + \nu) F_1(h) \right] \]

(22)

where \( W_0 = W/E_0 \).

3. Polymer tribology

3.1 General characteristics of polymers

Such properties of polymers, as chemical inertness, self-lubricating behavior and low wear rate at dry friction, have made them promising for tribological applications (Myshkin and Kovalev, 2009). Polymers may be divided into the following three groups: thermoplastic polymers, thermosetting ones and elastomers. Thermosetting polymers are the rheological parameter. Substituting equation (21) in equation (19), we get a parametric system of equations, describing the temperature dependence of the RCA. This system involves equation (21) and modified equation (19) in the form:

Thermoplastic polymer-based materials have found thermoplastic polymers, thermosetting and elastomers. Thermosetting polymers are stronger and stiffer than thermoplastics, but they do not show a melting phenomenon and are more difficult to process and shape. Thermosets include phenolic materials, epoxy resins and polyimides. Thermoplastic polymers are most widely used in tribological applications.

The overview of various polymers used in tribology (Myshkin et al., 2015) and their properties are given in Table I.

Thermoplastic polymer-based materials have found applications mainly for their self-lubricating properties. Because of their poor thermal conductivity and high thermal expansion, their applications should be carefully selected by taking account of load and velocity limits preventing the softening. Thermosetting polymers serve as matrices of materials for brakes and clutches. Polymer nanocomposites promise wide choice of applications.

Among the thermosetting polymers used for antifriction applications are polyimides, which have a high operating temperature (up to 220-260°C). Polyamides are used to fabricate sliding bearings with reinforcing fillers and dry lubricants. They are also good for polymer gears and thin polymer coatings (Kirupasankar et al., 2012). Polyolefins are widely used as matrix for antifriction composites and additives to other polymers, and even their disadvantage is low thermal resistance. Polymer gears, bushings and sliding bearings are often made of polyformaldehyde, polycarbonate and polyarylates. Thermosetting polymers also serve as matrices of materials for brakes, clutches and other frictional units (Wu et al., 2012).

Epoxies 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. 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 (Rodgers and Waddell, 2013).

3.2 Tribological behavior of polymers

The changes in the friction layer mainly arise from mechanical and chemical origin. Polymers due to their specific molecular structure are more sensitive to these factors. The great diversity of the friction and wear mechanisms and their interrelation make impossible, the rigorous classification of friction and wear processes for polymer materials. For example, when a polymer with visco-elastic behavior slides over a hard rough surface, the energy dissipation is caused by the high hysteresis losses. In this case, the deformation component of friction is governed by the

<table>
<thead>
<tr>
<th>Material</th>
<th>Friction coefficient</th>
<th>Operation temperature, °C</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aliphatic polymides</td>
<td>0.2/0.5</td>
<td>−40/+85</td>
<td>Low wear and high fatigue resistance</td>
<td>Water sorption, high coefficient of friction</td>
</tr>
<tr>
<td>Aromatic polyamides</td>
<td>0.1/0.3</td>
<td>−100/+200</td>
<td>Low wear, high fatigue resistance and heat stability</td>
<td>High cost; water sorption</td>
</tr>
<tr>
<td>Fluoroplastics</td>
<td>0.01/0.05</td>
<td>−269/+260</td>
<td>Low friction, resistance to aggressive media</td>
<td>Creep and low mechanical strength</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.2/0.5</td>
<td>−60/+125</td>
<td>Rigidity and resistance to aggressive media</td>
<td>Low fatigue strength</td>
</tr>
<tr>
<td>Polyacetals</td>
<td>0.1/0.3</td>
<td>−50/+120</td>
<td>High wear and fatigue resistance</td>
<td>Abrasive effect due to high rigidity</td>
</tr>
<tr>
<td>Polyolefins</td>
<td>0.1/0.3</td>
<td>−100/+100</td>
<td>High resistance to aggressive media</td>
<td>Low mechanical strength</td>
</tr>
<tr>
<td>Polyalkylene terephthalate</td>
<td>0.1/0.3</td>
<td>−20/+115</td>
<td>Resistance to aggressive media and heat resistance</td>
<td>Sensitivity to hot water</td>
</tr>
<tr>
<td>Thermoplastic elastomers</td>
<td>0.3/0.6</td>
<td>−60/+120</td>
<td>High elasticity and resistance to ambience</td>
<td>High friction and low mechanical strength</td>
</tr>
<tr>
<td>Polyetherether ketone</td>
<td>0.2/0.4</td>
<td>−30/+250</td>
<td>High heat and ambient resistance and γradiation</td>
<td>High cost</td>
</tr>
<tr>
<td>Polyphenylene sulfide</td>
<td>0.2/0.5</td>
<td>−30/+220</td>
<td>High wear and fatigue resistance</td>
<td>High cost</td>
</tr>
</tbody>
</table>
elastoplastic hysteresis. The adhesion component of friction comes from the adhesive bonds formed between the surfaces in the friction contact. It is believed that for polymers, the adhesion (molecular) component exceeds much the mechanical one (Bowden and Tabor, 1964).

It is well known that the friction force is proportional to the normal load, and experiments have shown that this law in general is valid for polymers (Myshkin and Kovalev, 2009), such as poly-tetrafluoroethylene (PTFE), poly-methylmethacrylate (PMMA), poly-etheretherketone (PEEK), poly-ethylene (PE) and others, in a range of load from 1 to 100 N. Similar behaviour of poly-dimethylsiloxane (PDMS) and poly-methylmethacrylate (PMMA) was even observed at micro/nanotribological characterization (Tambe and Bhushan, 2005). The reinforcement of PMMA by SiO₂ or TiO₂ can significantly reduce the friction coefficient, up to 0.09, and increase the lifetime of polymer coating (Gu et al., 2004). The semi-crystalline polymer as PEEK is one of the most explored polymer in recent years (Bijwe et al., 2013). PEEK has demonstrated the beneficial effect of solid lubricants and short-fiber reinforcement on its wear performance (Friedrich et al., 1995). Wear performance of functionally graded PEEK polymer composites with PTFE solid lubricant is studied in detail (Friedrich and Reinicke, 1998).

The most illustrative example of a polymer substance as a solid lubricant is PTFE. Pure PTFE is rarely used as a dry bearing material because of its high wear rate and low creep strength. The exceptions can be found in civil engineering: the bearing pads supporting bridge spans often consist of a slab of PTFE well confined in a shallow cast iron to prevent extrusion under very heavy bearing loads (Glavatskii and Fillon, 2006). A friction coefficient is about 0.02 under these conditions and permits thermal expansion and contraction of the span without imposing undue stresses on the structure.

Antifriction PTFE-based materials contain various fillers that improve the strength properties of the matrix polymer (coke, soot, fibers, metal powders, graphite, molybdenum disulfide etc). It has been found that PTFE is transferred in the form of thin flakes. Figure 3(a) presents the semi-crystalline nature of PTFE with crystalline layers and amorphous regions between them. Figure 3(b) presents the AFM image of the PTFE surface after friction tests. Crystallites are clearly seen on the friction surface, and they are disordered which proves their motion at friction. Such motion provides the reduction of the friction coefficient and transfer to the counterface (Aderikhin and Shapovalov, 2010; Pooley and Tabor, 1972). Other applications of PTFE are linings with a metal substrate and an upper porous layer impregnated with PTFE-based composition. Bearings with such linings are the most efficient under heavy-duty operation.

4. Polymer nanocomposites

In most of cases, the high thermal expansion, low thermal conductivity and creep of pure polymers limit their use. These problems are largely overcome if the polymer takes the form of a thin layer firmly bonded to a substrate. Load-carrying capacity and dimensional stability are good, so conventional bearing clearances may be used. There is a continuous progress in polymer science, and each year, new polymer materials are synthesized. Great advances are achieved in combination of polymers with other materials (Friedrich and Reinicke, 1998).

Ultraplain polymer films, monolayers and nanocomposite polymer layers were explored as molecular lubricants aimed at the modification of the interfacial properties at the nanoscale (Kovalev and Tsukruk, 2013). Polymer films and nanolayers can be considered as a kind of two-dimensional nanomaterial. Substantial studies have been devoted to nanolayers (such as poly[styrene- b-butadiene]; poly[styrene-b-butadiene-b-styrene]; poly[styrene-b-(ethylene-co-butylene)-b-styrene], SEBS) because of their potential applications in many technological areas, including coatings, adhesives and membranes. These films self-organize in a variety of microdomain structures. The morphology of ultrathin polymer films strongly depends on the grafting density and molecular mass of nanolayers (Luzinov and Tsukruk, 2002).

The wear resistance of the nanolayers was estimated at the contact of a steel ball and local pressures/velocities comparable with that of microelectromechanical system (MEMS) operating conditions. In this method, a sharp increase in the friction forces indicates surface failure. Experimental data are shown for the trilayer structures in comparison with a neat

Figure 3 Excellent tribological properties of PTFE are explained by the semi-crystalline structure of PTFE

Notes: (a) A schematic of the microstructure of PTFE; (b) AFM-image of PTFE friction surface
silicon surface and self-assembled monolayer (SAM). During the test, the contact pressure reached 1.2 GPa, which was much higher than the yield strength of most polymers. Under these conditions, the wear resistance was controlled by the ability of the surface to self-heal, rather than by direct elastic resistance. Silicon reference sample failed almost immediately, as shown in Figure 4, and alkylsilane SAM failed after 900 cycles. The trilayered polymer structure has shown much lower and stable wear, and was worn after 3,000-3,500 cycles, which is rather good for MEMS applications.

Polymer nanocomposites are typically formed while filling the polymer by particles or fibers (Pesetskii and Bogdanovich, 2013). Carbon nanofillers are quite attractive for such purposes but homogenous distribution of nanotubes and fullerenes can be achieved in extrusion of polymers with high shear rates. Nanofiller particles interact actively with macromolecules and often change temperatures of major relaxation transitions, particularly cause an increase in glass transition temperature. This allows the use of use polymer nanocomposites at higher warming-up temperature in the boundary layer of the material. Owing to their highly developed surfaces, nanofillers can much influence the course of tribochemical processes: thermal oxidation and mechanical degradation of macromolecules become inhibited; cracks “heal”, and the macromolecular rearrangement accelerates to form cellular structures that are resistant to wearing (Aly, 2012). Nanocomposites with metal fillers can be formed by introduction of particles into the melt matrix formed by mixing them with the polymer powder and further melting and pressing (Pesetskii et al., 2013). 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.

Polymer–clay nanocomposites (Pesetskii et al., 2008) are prospective because of their low price and availability of mass production. However, the laminated silicates should be compatible with the polymer matrix, so their surface should be modified by surface-active substances. Chemosorption of clay nanofillers reduces the surface energy and increases the wettability of surface.

Figure 5 illustrates the scheme of forming polymer–clay composite. The main assumption is that the generation is governed by direct intercalation of a polymer melt into the galleries of a layered clay mineral. It occurs if the particles were treated with a speciality surfactant. The important factors affecting the extent of penetration into galleries of mineral particles are closely linked to the nature of surfactants and polar interactions of the nanoclay and polymer matrix.

The selected mechanical properties and wear characteristic of the polymer–clay composites in Table II are given. The composition was processed using the solid-phase extrusion method where polyamide 6 (PA 6) was used as the base polymer. The clay used was N+-montmorillonite (MMT) with a cation-exchange capacity of 95 mg-eq/100g; it was used in two versions: original substance and that modified by octadecylamine (ODA). The PA6/clay composites produced by the solid-phase extrusion method have showed much higher deformability ε and have also shown high abrasive resistance and wear resistance when sliding over steel.

As it was revealed (Pavlidou and Papaspyrides, 2008), clay, added to polymer matrix, enhances their heat resistance, thermal resistance and the resistance to thermooxidative degradation. Improved barrier features of nanofillers prevent diffusion of oxygen into the polymer and escape of the volatile products of thermoysis. The prolonged heating of a nanocomposite can strengthen the barrier quality, resulting in baking of the silicate in the surface layer of the sample and creation of a networked structure.

The treatment of polymer composite with the surfactant, unlike that with water, ensured a higher level of adhesion between the phases, and hence, increased wear resistance (Pesetskii et al., 2008). Thus, much improved wear resistance of polymer/clay nanocomposites can only be achieved by combining two factors, such as fine dispersion of layered mineral platelets in the polymer matrix and a high level of adhesion between the phases. The latter feature depends on the right choice of surfactants for treating the clay.

Table II Properties of polymer–clay composites

<table>
<thead>
<tr>
<th>Composition (Wt.%)</th>
<th>σr (MPa)</th>
<th>ε (%)</th>
<th>labr. \times 10^{-3}, g/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>PA 6/nanoclay (MMT)–3%</td>
<td>75</td>
<td>76</td>
<td>2.8</td>
</tr>
<tr>
<td>PA 6/nanoclay (MMT–ODA)–3%</td>
<td>86</td>
<td>53</td>
<td>4.0</td>
</tr>
</tbody>
</table>
5. Conclusions

This short survey has shown basic roles of contact mechanics and mechanical properties of polymer and polymer composites affecting their friction and wear. Surface interaction influences the adhesion component of the friction force and contact mechanics tasks were considered in a case of viscoelastic behavior of polymer. Even for the adhesion component, deformation loss can greatly control the friction, especially for elastomeric polymers as it was discussed here.

Extensive studies have developed the field of tribology in which the polymer-based materials can be applied as coatings and solid lubricants. The latter are used either in the pure form or as composites. The thin polymer films are prospective boundary lubricants in the area of memory storage devices, solving a number of the important problems in contact mechanics tasks were considered in a case of viscoelastic behavior of polymer. Even for the adhesion component, deformation loss can greatly control the friction, especially for elastomeric polymers as it was discussed here.

Polymer tribology has grown quickly following the wide application of polymer-based materials in engineering because of the use of different fillers, greatly improving the tribological behavior of neat polymers. Polymers with nanofillers have found applications in various high-tech areas. Those of them that are produced at commercial scale are taking over the areas traditionally occupied by conventional materials.

Further progress in polymer tribology should be based on solving a number of the important problems in contact mechanics, surface physics and tribo-chemical reactions.

References


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