Evaluation of Fatigue Wear and the Nature of the Destruction of Polymeric Materials

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***Abstract*—As the result of instrumental studies of multicomponent polymeric materials' tribotechnical properties (coefficient of friction, temperature, and microstructure of working surfaces), the leading role of fatigue wear of polymeric materials during their friction for metal is confirmed, and the ability of the filler to block mechanically fracture cracks during polymer friction are experimentally substantiated. The effect of impact stress on friction and wear of polymer composite materials is also considered. It has been established that the materials of the oilseed group are highly resistant to frictional and bulk fatigue and are able to work for a long time without failure under the cyclical dynamic nature of loading.**

Keywords—wear, tribotechnology, profile record, microcrack, nylon, fiberglass, lubricate, counterbody, adhesion, homogeneity

I. Introduction

Numerous studies on this topic were conducted. Firstly by Griffith, and then by domestic scientists, it was proved that the strength of polymeric materials, measured experimentally, is 2-3 times of magnitude lower than theoretically supposed [5, 7]. This discrepancy in the strength is explicated by polymer heterogeneity over the entire volume, the presence in the surface layers and in the depth of the material of a large number of defects such as microcracks, pores, dislocations, and lattice strains. These imperfections in the structure of a polymeric material are potential centers for the generation of microcracks, and some of them are microcracks themselves. In the mouths (tops) of these cracks under the action of static or dynamic (friction force) loads, overvoltages occur, causing further development of cracks into the one dominant and even destruction of the section (or separation of its fragment) if this critical stress exceeds theoretical strength.

The discreteness of the contact of the rubbing bodies causes high-frequency shock pulses in the areas of microasperities and in the adjacent zones. However, due to the insignificance of microasperity sizes and the elastic properties of polymers, the shock wave has a small amplitude and for acquired surfaces its role in fatigue wear cannot be assessed separately from the influence of the nominal load in the contact. In addition to the above impulses of transverse deformations, the surface layers of the sections of the road constructions, transport machines and processing facilities that are in frictional contact are subjected to time-varying (dynamic) loads that can manifest themselves in the form of impact. Correct prediction of operational fatigue wear resistance and strength properties of antifriction materials is impossible without studying the effect of loading dynamics on them.

II. Methods and Materials

To study the effect of speeds (dynamics) of loading on the work of a friction pair, such materials were recommended that are suited for the most loaded friction unit of road construction and agricultural machines – the gimbal joint: antifrictional polymer composite “Maslyanit KSC”, “Maslyanit KS-2”, and also the most characteristic representative of antifrictional polymer materials that do not contain fibrous filler – “Maslyanit D(S-1)”. For comparison, nylon without filler was tested. The tests were carried out on a standard friction machine MI-1M. To compare the effects of dynamic loading and shock loads, two types of samples were made: with eccentricity and with a protrusion on the working surface.

On an end-type friction machine on a smooth steel surface, an unfilled nylon was tested, as well as modified polymer composites: “Maslyanit KS-1”, “Maslyanit D (S-1)”, and ATM-1. As an evaluation criterion, a comparative analysis of indicators characterizing the tribotechnical properties of a friction pair in dynamics, as well as a visual inspection of the state of the surfaces of the parts, was carried out.

III. Results

It is known that the theory of Griffith considers only the “athermal” mechanism of destruction. Studies of the time dependence of the strength of solids from thermal fluctuations of atoms that were carried out by Zhurkov and his staff show the temperature dependence of the durability of the material, which is described by the equation [2]:

$$\tau = \tau_0\left[\exp\frac{U_0-\gamma\sigma_1}{RT}+\exp\frac{U_0-\gamma\sigma_{\Pi}}{RT}\right]-\tau_{23} \qquad (1)$$

For a polymer composite material with a large number of acts of cracks initiation and blocking, equation (1) can be transformed in the following form:

$$\tau = \tau_0\left[\exp\frac{U_0-\gamma\sigma_1}{RT}+\exp\frac{U_0-\gamma_2}{RT}+...+\exp\frac{U_0-\gamma\sigma_{\Pi}}{RT}\right]-\sum_{i=1}^{\Pi}\tau_{\Pi}^{1} \qquad (2)$$

where τ_0 – is a constant, close in value to the period of thermal oscillations of atoms; U_0 – is the activation energy of the elementary act of destruction; γ – is the coefficient determining the nature and structure of the material; σ – is the stress applied to the sample; R – is the Boltzmann constant; T – absolute temperature; τ_{Π}^{1} – the time of unrealized stock of durability of the material (particles at the time of the n-th act of blocking the crack).

Thus, according to Zhurkov, as a result of thermal fluctuations, the kinetic energy of atoms increases and, if this energy exceeds the energy of chemical bonds, their rupture occurs.

The participation of surface layers of a polymeric material in a frictional contact promotes an increase in thermal fluctuations that, after a certain number of deformation cycles, break interatomic bonds. As a result of such an impact, the emergence or further development of an existing crack and the destruction of the material or separation of its fragment from the base occur. A number of authors have found that one of the ways to reduce fatigue wear of rubbing polymers is to reduce the thickness of the deformable (fatigued) material under the friction of the working layer, which can be achieved by increasing the hardness of the material (degree of crystallinity) [4, 5]. As it is known, increasing the hardness of a polymer is achieved by modifying it with metal ingredients (powders) and fibers.

From this point of view, testing a pure polymer in comparison with multicomponent polymeric materials presents a particular interest.

Continuing the previous studies [6], we tested an end-type friction machine on a smooth steel surface (Ra = 0.65 μm) at a speed of 0.5 m/s, a pressure of 98104 Pa (fan cooling) unfilled nylon, and also antifrictional polymer composites: “Maslyanit KS-1”, “Maslyanit D (C-1)” and ATM-1. As an evaluation criterion, a comparative analysis of indicators characterizing the tribotechnical properties of a friction pair in dynamics, as well as a visual inspection of the state of the surfaces of parts, was carried out.

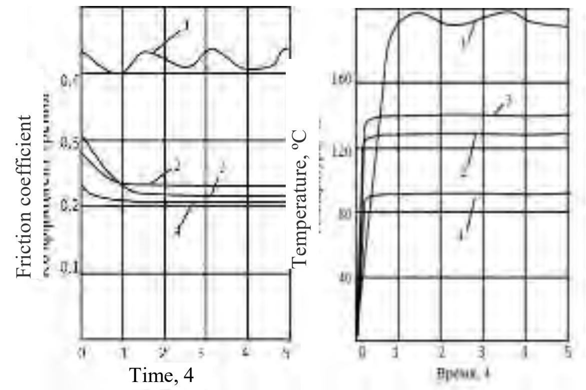

Fig. 1. The effect of testing period on the antifriction properties (a) and temperature in the friction zone (b) of nylon (1), Maslyanit KS-1 (2), Maslyanit D (S-1) (3) and ATM-1 (4).

For filled compositions, despite the actual insignificance of scaly wear particles, fluctuations in the friction coefficient and temperature under the friction surface of the studied materials (Fig. 1, a and b, curves 2, 3, 4), representing monotonically repeated with a “latent” [8] period curves allow to make a conclusion about the fatigue nature of the wear of these compositions during friction on metal. An additional confirmation of this is the micrographs (Fig. 2, a) with the transverse orientation of the microcracks to the friction tracks. By blocking the path of a developing crack, the filler increases the number of deformation cycles required for particle separation (Fig. 2, b).

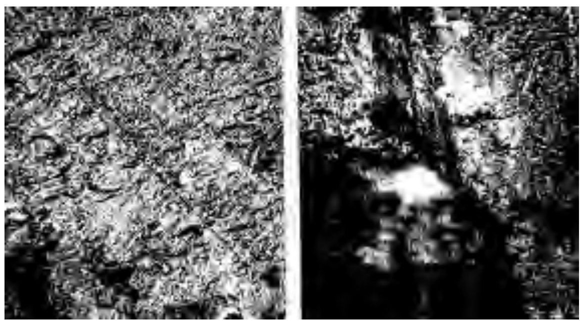

Fig. 2. Micrographs of friction surfaces of Maslyanit D (S-1) ×140 (a) and Maslyanit KS-1 ×1000 (b).

Fig. 3. The surface of the nylon sample after fatigue wear (a) and micrograph (x 5000) of the subsurface layer topography (b).

A similar conclusion about fatigue wear on periodically appearing peaks can be made for nylon (Fig. 1, curves 1).

However, in addition to extremely large values of temperature and coefficient of friction, the appearance of the friction surface and its wear products differ significantly from composite materials. This wear pattern of nylon can be explained by the following reasons. As a result of the work hardening and hardening of the surface layers during friction [7] at a depth of 0.2-0.5 mm from the surface, maximum tangential stresses arise, causing the formation of fatigue cracks in these areas. Studying the issue of the location of primary fatigue cracks [3], E.A. Fedorchuk experimentally found that during rolling friction of pure polyamides, fractures can occur at different depths from the working surface, depending on the contact load. In contrast to pure polyamides (nylon), filled nylon is less susceptible to plastic deformation and is work-hardening due to the higher modulus of elasticity of filler (fiberglass, metal powders). As a result, the likelihood of cracks in multicomponent materials is higher on the surface, and in single-component materials – below the surface. However, if in the compositions as a result of mechanical “blockade” a crack is for a long time incapable of detaching a particle from the base material, in clean ones it can easily spread in subsurface layers weakened by hardening along the entire friction track, causing in some cases bulk fatigue and part destruction (Fig. 3.). This is an additional confirmation of the dominant fatigue nature of wear of nylon.

Since the node we used allowed us to continuously measure the total wear of a friction pair, for a differentiated assessment of the wear of polymeric materials and metal counterbodies from the surface of the latter in control experiments, profilograms were taken (Fig. 4.). In order to study the features of the process of running in a metal-polymer pair, the relief of the counterbody surface was studied. For this, a profilograph was used – a profilometer, model P-236.

Profilograms were taken from the same place before the tests, after 1 h and 5 h of friction pair work. The vertical increase is 10.000 times, the length of the integration path is 1.6 mm, and the tracing speed is 0.6 mm/min. As a result of profilometry of the inactive surfaces of the counterbody (curves 1 and 4) and surfaces involved in frictional interaction with the Maslyanit KS-1 (curves 2 and 3) and with ATM-1 (curves 5 and 6), it was found that during the first hour of operation there is wear of the counterbody (curves 2 and 5), equal to 5-7 and 3-4 μm, respectively. The profilograms taken after the 5-hour experiment (curves 3 and 6) are identical to the curves obtained after the first hour of the test, which indicates the insignificance of further wear of the metal counterbody and the completion of the running-in process of friction pairs after 1-2 hours of work.

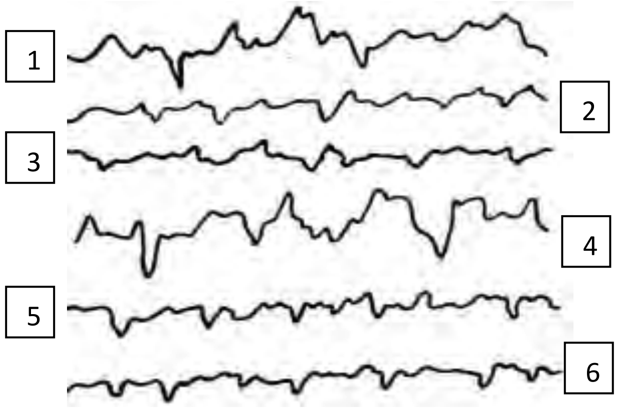

Fig. 4. Profilograms of the surfaces of the steel counterbody before the tests (1, 4), after one (2, 5) and five (3, 6) hours of tests, which worked in conjunction with Maslyanit KS-1 (2, 3) and ATM-1 (5, 6).

The increased wear of the steel surface in contact with the unfilled polymer — nylon can be explained by the high density of free radicals generated during polymer friction, which cause plasticization and dispersion of the metal [1] (Table I).

TABLE I. WEIGHT WEARING OF CONTRBODIES UNDER FRICTIONS WITH POLYMER COMPOSITORS

No	Sample material	Total weight wear, mg	
		After 1 h	*After 5 h*
1	Nylon	12.5	19.3
2	Maslyanit D (S-1)	4.0	5.1
3	Maslyanit KS-1	10.4	11.2
4	ATM-1	6.1	6.8

In filled compositions. the density of free radicals (the proportion of the polymer) is significantly lower. In addition, the “third body” – boundary lubricating layers, consisting mainly of a complex mixture of solid and plastic lubricants, filling juvenile surfaces and leveling the relief of the friction track (Fig. 5.). Shields the metal surface, thus inhibiting the process of passivation and dispersing its working layers.

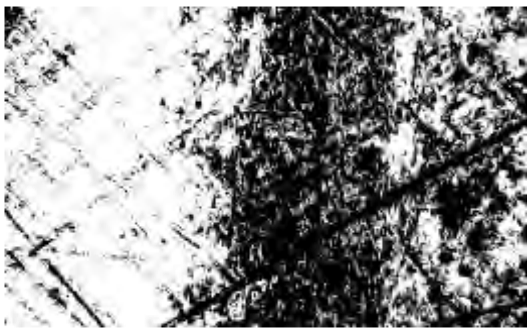

Fig. 5. Boundary lubricating film along the friction track, shielding the surface of the metal counterbody.

Despite the fact that the generation and adsorption of the boundary film on the steel surface occurs from the very beginning of the sliding friction process. during the period of running-in, the microprotrusions of the steel surface due to local pressures are less protected from the dispersing and plasticizing effect of the free radicals of the matrix of the composite material (Fig. 6 a).

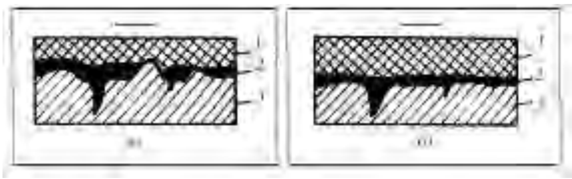

Fig. 6. Scheme of the reliefs of the sample (1) and the counterbody (3) during running-in (a) and steady-state friction (b); 2 – boundary lubricating film.

The relatively large wear of the metal surface in contact with the glass-fiber composition (Table I) can be explained by less elastic deformation and high hardness of glass fiber. This causes an increase in local stresses at the contact of the microprotrusion – glass fiber, “film starvation”, and partial micro-cutting. After completion of the process of running in a friction pair, the removal of microprotrusions and the relief leveling of the surface of the metal counterbody decrease transverse deformations and fatigue of the surface, working polymer layers (Fig. 6 b), which reduces the wear of both parts of the friction pair (Table I).

As is known from the Physical Chemistry of polymers [5, 9, 10], in pure polymers placed in a force field, the process of orientation of parts of chain macromolecules rolled into globules or assembled in bundles, associated with a complex of relaxation phenomena and structural changes of the material, occurs. The orientation of the deformed polymer leads to the hardening of the tip of the fracture crack. Therefore, if the orientation rate exceeds the crack growth rate, then hardening will stop the crack growth for a while. If the velocity of the force field is high, then the orientation will not be able to get ahead of the crack growth, which will lead to the destruction of the surface (wear) or polymer volume. It follows that the critical values of the magnitude and rate of load application for homogeneous polymers are determined by their relaxation capabilities.

We have found that in the process of friction of materials the orientation of their working surfaces occurs, which gives them a high wear resistance. This is correlated with the established by G.A. Gorokhovsky and his staff orientation of the elements of the molecular structure of the working polymer layer: PE, PTFE, PKA and CFF and increasing their wear resistance at low loading rates [3].

The tests were carried out on a standard MI-1M friction machine using the scheme shown in Fig. 7. To compare the effects of dynamic loading and shock loads. two types of samples were made: with eccentricity and with a protrusion on the working surface. The load in examining the impact was taken to be 647 H, for the case of non-impact dynamic loading, 647 and 1254 H, with the increase in these efforts due to eccentricity of 8-12 H being 53-80 N/s. The decrease in speed and load as a result of sample wear was neglected, since this factor influenced the samples equally in all experiments.

The results of testing materials at nominal loads 647 and 1254 H are presented in Tables II and III.

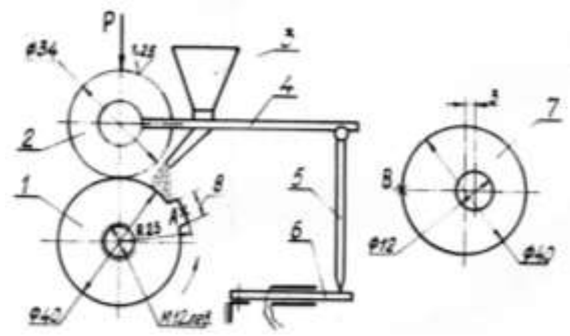

Fig. 7. Friction unit for friction machine MI-1M for impact wear.

TABLE II. THE RESULTS OF TESTING MASLYANITS WITH DYNAMIC LOADING (V = 0.42 m/s)

Materials	Wear rate (mm/h) under load		Friction coefficient under load	
Maslyanit KSC	0.85	1.76	0.06	0.068
Maslyanit KS-2	2.04	3.11	0.08	0.082
Maslyanit D(S-1)	3.73	7.90	0.067	0.075

As can be seen from the table, Maslyanit KSC has minimal wear. The same ratios of material wear have been preserved when tested on other machines. Somewhat different laws are obtained from friction coefficients: being in the region of smaller values, they increase for all materials with increasing load on the roller, although the pressure increases by an increase in the area of actual contact, but not proportionally to the load, but by a smaller value. The fact of a general decrease in the friction coefficient can be explained by a better extrusion of the plasticizer into the friction zone, a decrease in the adhesive component and a lower value of the coefficient of overlap, which has a favorable effect on the temperature mode of the friction process. The increase in friction coefficient with increasing load can be explained by the increase in wave height of the deformed material running in front of the roller.

Fig. 8. Samples of Maslyanits: D (C-1) (1). KS-2 (2) and KSC (3). tested under dynamic loading (p = 1254 N)

The wear of all samples began in the areas of maximum load. The surfaces of the worn samples (Fig. 8) and the scaly shape of the wear particles indicate the fatigue nature of wear.

It has been established that with the introduction of fibrous fillers into the material or with a decrease in the load, the sizes of wear products decrease. In the absence of filler, a particle of wear may be commensurate with the dimensions of the sample friction track. So, for the case of rolling friction PA610, according to a similar scheme without a dynamic load, E.A.

Fedorchuk [5] obtained that the wear particle with a triangular cross-section encompasses the entire friction track and has a thickness of up to 3 mm, depending on pressure.

In the case of dynamic loading, the sample was struck twice in one revolution: when the roller came into contact with the protrusion and jumped off of it, the impact of which turned out to be stronger. In this place a crack appeared on the sample from nylon, which led to the destruction of the sample after 5 min of work (Fig. 9).

TABLE III. RESULTS OF MASLYANITS TESTING WITH SHOCK LOADING

Materials	Wear rate (mm/h)
Maslyanit KSC	0.73
Maslyanit KS-2	1.50
Maslyanit D(S-1)	2.62
Nylon	The sample was destroyed

Fig.9. Samples of Maslyanit KSC (1). Maslyanit D (S-1) (2) and nylon (3). tested with shock loads.

Thus, the test results show that clean nylon, despite the homogeneity and greater elasticity than the Maslyanit KSC is more prone to volume fatigue failure during cyclic impact.

IV. CONCLUSION

The conducted studies confirm the leading role of fatigue wear of polymeric materials during their friction on metal, and also experimentally substantiate assumptions about the ability of the filler to block mechanically fracture cracks during friction fatigue of the polymer.

It has been proved that with the introduction of fibrous fillers into the material or with the load decrease, the sizes of wear products decrease. As filler lacks, a particle of wear may be commensurate with the dimensions of the sample friction track. So, for the case of rolling friction PA610 according to the scheme without dynamic loading, it is obtained that the wear particle with a triangular cross section covers the entire friction track and has a thickness of up to 3 mm depending on pressure.

The test results show that clean nylon, despite the homogeneity and greater elasticity than the lubricant of the Maslyanit KSC, is more prone to volume fatigue failure during cyclic impact. This circumstance is of fundamental importance for confirming the mechanism for blocking fatigue cracks by solid filler particles. In homogeneous polymers, as noted above, the stress peaks that occur at low loading rates are smoothed by relaxation processes, seeking to bring the system into equilibrium. Molecular chain orientations occurring in this case can halt the growth of fatigue cracks. As can be seen from the study of the impact of shock friction effects, the ability of oriented portions of nylon to block the growth of cracks is low. Studies have shown high wear resistance and contact strength of highly filled lubricants. The rate of propagation of a fatigue crack, determined by the rate of loading of the polymer, can be effectively reduced by the introduction of solid particles with the ability of additional stress relaxation in the area of the crack tip. At the same time, such a mechanism for blocking cracks does not exclude, but favors the orientation of molecular chains and packs due to the delay of cracks along the front of its propagation.

From the conducted research, an important conclusion follows: the materials of the Maslyanit group are highly resistant to frictional and bulk fatigue and are able to work for a long time without failure under the cyclical dynamic nature of loading. The conducted studies also confirmed the high tribotechnical properties of the composite material Maslyanit KSC, which, as a result of surface “cementation,” has an increased hardness of the surface layers and high impact strength of the bulk layers.

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