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Increase in the Wear Resistance of Polytetrafluoroethylene on Filling with Disperse Particles

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Abstract—The reduction in the wear of polytetrafluoroethylene (PTFE) in the presence of disperse filler is analyzed. It is found that decrease in the load on the PTFE matrix increases the mechanical component in the wear of PTFE composites. The calculations are confirmed by experiments on the wear of F4K15M5 composite.

Keywords: wear resistance, wear rate, linear wear, polytetrafluoroethylene, composites, friction, polymers
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Polytetrafluoroethylene (PTFE) is not generally used in frictional systems in its pure form, on account of its low wear resistance [1]. As a rule, polymers form films in friction at a metallic body, as a result of adhesion [2]. In the wear of PTFE, transfer of the polymer is due to the destruction of its strip structure [3]. Individual particles (length around 0.3 μm and width 20–30 nm) fill the microdepressions on the metal surface and are partially transferred to the microprojections [4]. That reduces the frictional coefficient in the polymer–steel pair. The small adhering particles eventually form a layer, which, on reaching a specific size, are removed from the contact surface in the form of a wear particle. To reduce the wear, fillers are added to PTFE, with considerable increase in its wear resistance: the fillers slow the propagation of subsurface cracks and form a thin protective film [3, 5].

No theoretical explanation has been proposed for the sharp decrease in the wear of PTFE in the presence of disperse filler. In the present work, we analyze possible wear mechanisms with a view to developing a new approach to the creation of PTFE composites. On the basis of an empirical wear law, we propose an explanation for the reduced wear of the PTFE in the presence of disperse filler.

We may write an empirical wear law in terms of the linear wear rate I_h [6]

$$I_h = I_{h\mathrm{mc}} + I_{h\mathrm{m}} = ap^2 v \mathrm{e}^{-bpv} + cp(e^{dpv} - 1), \qquad (1)$$

where $I_{h\mathrm{mc}}$ and $I_{h\mathrm{m}}$ are the mechanochemical and mechanical components of the wear rate; p is the contact pressure; v is the slip velocity; a, b, c, and d are constants.

A physical model of the wear of polymer composites was proposed in [6]. The model takes account of the structural parameters that affect the load distribution at the polymer–filler contact surfaces. For the sake of convenience, we write the linear wear rate of the PTFE matrix in the form $I_h^m = I_{h\mathrm{mc}}^m + I_{h\mathrm{m}}^m$, where $I_{h\mathrm{mc}}^m$ and $I_{h\mathrm{m}}^m$ are the mechanochemical and mechanical components of the wear rate for the matrix. For the filler, correspondingly, $I_h^f = I_{h\mathrm{mc}}^f + I_{h\mathrm{m}}^f$, where $I_{h\mathrm{mc}}^f$ and $I_{h\mathrm{m}}^f$ are the mechanochemical and mechanical components of the wear rate for the filler. The dimensional coefficients in the empirical wear law are a_1, b_1, c_1, d_1 for the matrix and a_2, b_2, c_2, d_2 for the filler. We may now write the linear wear rate of the composite in the form

$$\begin{aligned} I_{h\Sigma} &= I_{h\mathrm{mc}}^m + I_{h\mathrm{m}}^m + I_{h\mathrm{mc}}^f + I_{h\mathrm{m}}^f \\ &= \beta^2 p^2 v a_1 \mathrm{e}^{-b_1 p v} + \beta p c_1 (\mathrm{e}^{d_1 p v} - 1) \qquad (2) \\ &+ (1-\beta)^2 p^2 v a_2 \mathrm{e}^{-b_2 p v} + (1-\beta) p c_2 (\mathrm{e}^{d_2 p v} - 1), \end{aligned}$$

where β is the contact pressure on the matrix.

Polymer composites based on PTFE have the spatial structure of the filler [7]. This may be attributed to the manufacturing process employed, which includes the mixing of the large granulated PTFE particles and smaller filler particles. The micronic filler particles form single-layer structures around the polymer particles in most cases. On introducing nanoparticles in the matrix, we obtain multilayer filler structures [8]. In the present work, we analyze the wear resistance of a composite with a single-layer filler structure.

Consider a model composite with a PTFE matrix containing micronic particles of AG-600 SO5 carbon filler [9]. To simplify the calculation of the load distribution, we assume that the polymer and filler particles

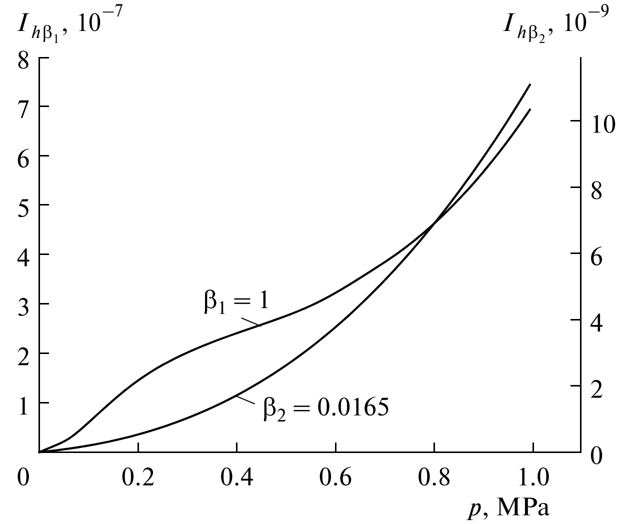

Fig. 1. Dependence of the wear rate I_h of PTFE on the pressure p when $\beta_1 = 1$, $\beta_2 = 0.0165$, and $v = 1$ m/s. In Eq. (2), $a_1 = 1.1 \times 10^{-11}$, $b_1 = 6.2$, $c_1 = 3 \times 10^{-12}$, and $d_1 = 0.2$.

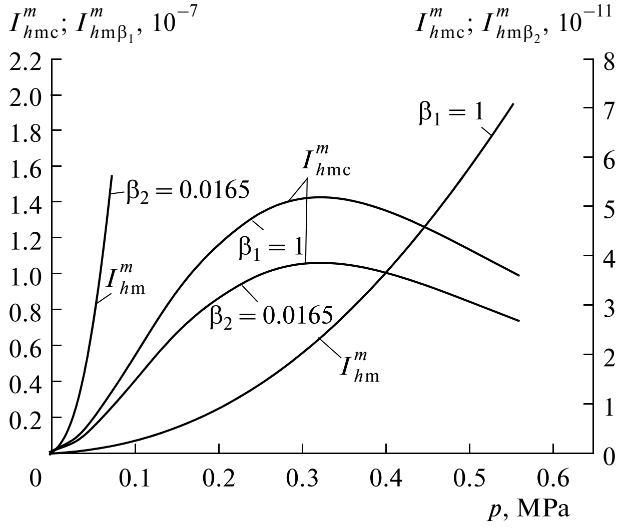

Fig. 2. Dependence of components $I^m_{h\text{mc}}$ and $I^m_{h\text{m}}$ of the wear rate of PTFE on the pressure p at various values of β, when $v = 1$ m/s, according to the first and second terms in Eq. (2). As in Fig. 1, $a_1 = 1.1 \times 10^{-11}$, $b_1 = 6.2$, $c_1 = 3 \times 10^{-12}$, and $d_1 = 0.2$.

are cubic (with faces r_p and r_f, respectively). In that case [7]

$$\beta = \frac{(1 - 0.7\varphi_f)}{(1 - 0.7\varphi_f) + 0.7\chi\varphi_{SK}\varphi_f}, \tag{3}$$

where φ_f is the filler concentration; $\chi = E_m/E_{f0}$; E_m is the elastic modulus of the matrix; E_{f0} is the resistance to deformation for the wall of the structure formed by the filler; φ_{SK} is the defect content of the wall.

For the wall of the structure formed by the filler, the defect content is [7]

$$\varphi_{SK} = \frac{\varphi_f r_p}{3(1 - \varphi_f) r_f}. \tag{4}$$

We assume the following dimensions: $r_p = 63$ μm; $r_f = 7$ μm. We also assume that $E_m = 0.45$ GPa and $E_{f0} = 220$ GPa, in accordance with [10].

When using micronic filler particles, as a rule, the optimal value of φ_f is around 20 vol % [11]. In that case, according to Eqs. (4) and (3), $\beta = 0.0165$.

To better understand the relative importance of the wear resistance of the filler particles and PTFE matrix in the composite and to determine the coefficients in the empirical wear law, we test PTFE and AG-600 SO5 carbon filler samples by the method in [12]. We select a steel 45 counterbody (State Standard GOST 1050–88). In Fig. 1, we show the pressure dependence of the linear wear rate according to the sum of the first two terms in Eq. (2) for pure PTFE (with $\beta = 1$) and for PTFE in the model composite (with $\beta = 0.165$).

Analysis shows that the linear wear rate of PTFE in the composite is about two orders of magnitude less than for pure PTFE. In addition, the dependence of I_h on p increases monotonically when $\beta = 0.0165$ but has a section with relatively stable I_h when $\beta = 1$ [7, 9]. For detailed analysis of this discrepancy, we plot the first and second terms in Eq. (2) individually.

When PTFE forms part of the composite, the amplitude $I^m_{h\text{mc}}$ is sharply less (by more than three orders of magnitude) than for pure PTFE. This is probably associated with the low rate of film formation on the counterbody, on account of the low load on the PTFE in the composite. In addition, it follows from Fig. 2 that the mechanical component of wear significantly predominates in the working load range for PTFE in the composite, while the mechanochemical component predominates for pure PTFE.

In Fig. 3, we show the pressure dependence of the linear wear rate for AG-600 SO5 carbon filler according to the sum of the third and fourth terms in Eq. (2).

To obtain the dependence of $I_{h\Sigma}$ on the pressure p on the basis of Eq. (2), it is incorrect to use curve *1* in Fig. 3, since the structure formed by the filler is not in contact with the counterbody during friction but with the transfer layer. We need to correct the coefficients of the mechanochemical wear component in the empirical wear law obtained from experimental data for AG-600 SO5 carbon filler so as to take account that it is present in the composite, where $\beta = 0.0165$.

The literature indicates that, in the wear of PTFE composites on steel, material is transferred to the counterbody from both the matrix and the filler [4].

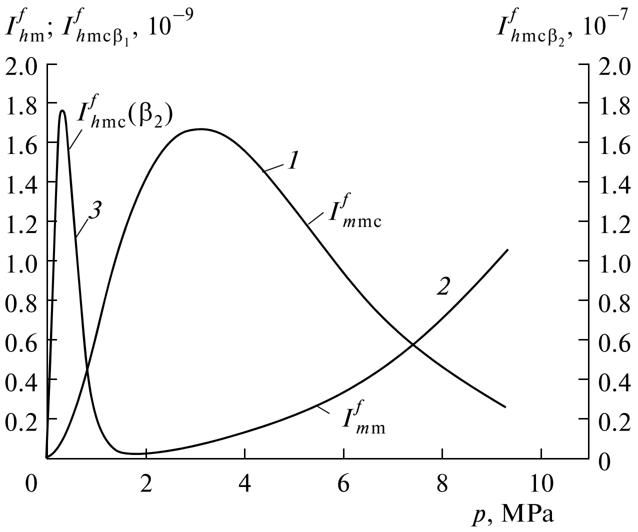

Fig. 3. Dependence of components I^f_{hmc} and I^f_{hm} of the wear rate of AG-600 SO5 carbon filler on the pressure p, when $\beta = 0$ (*1*, *2*) and 0.0165(*3*) and $v = 1$ m/s, according to the third and fourth terms in Eq. (2): (*1*, *2*) $a_2 = 1.3 \times 10^{-13}$, $b_2 = 0.65$, $c_2 = 5.4 \times 10^{-15}$, and $d_2 = 0.12$; (*3*) $a_2 = 1.3 \times 10^{-13}$, $b_2 = b_1 = 6.2$.

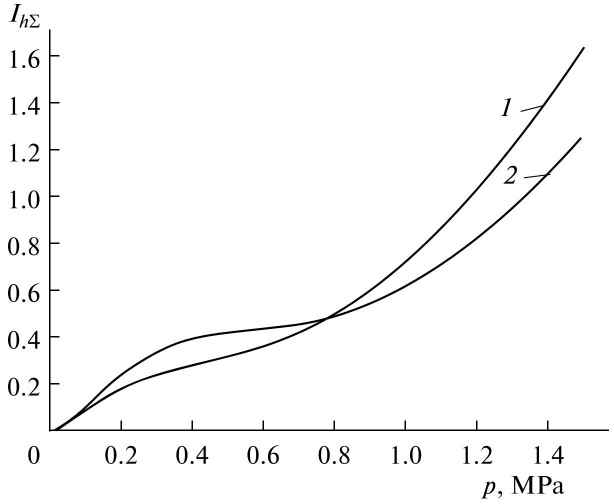

Fig. 4. Dependence of the total wear rate $I_{h\Sigma}$ on the pressure p, when $v = 1$ m/s: (*1*) for the model composite consisting of PTFE and AG-600 SO5 carbon filler ($a_2 = 1.3 \times 10^{-13}$, $b_2 = b_1 = 6.2$, $c_2 = 5.4 \times 10^{-15}$, and $d_2 = 0.12$; (*2*) F4K15M5 industrial composite ($a = 1.5 \times 10^{-13}$, $b = 5.5$, $c = 4 \times 10^{-14}$, $d = 0.125$).

This has been attributed to the remote action of the surfaces. Thus, the interaction force of the surfaces is unchanged over gaps of a few hundred nm, according to [13]. When a hard surface is covered with a screening polymer film, action over a distance of 100–150 nm is possible [14]. Since the thickness of the primary particles transferred to the steel is 20–30 nm, the presence of the film of transferred material may be disregarded in considering the transfer of filler to the counterbody, on account of remote action. However, in the presence of screening polymer films at the solid surface, the influence of the temperature of such films must be taken into account. We know that the adhesive strength of PTFE at steel depends considerably on the temperature [4]. In certain conditions, this may present the transfer of filler to the counterbody. Therefore, in the I^f_{hmc} term in Eq. (2), the coefficient b_2, which takes account of the influence of temperature on the wear, must be assumed equal to b_1. Then, the refined pressure dependence of the mechanochemical wear component for filler in the composite, corresponding to the third term in Eq. (2), takes the form of curve *3* in Fig. 3. Thus, the resulting curve is shifted to the pv range where wear of the matrix is also observed.

To verify our analysis of the contributions of the filler and matrix to the total wear of the PTFE composite, we compare the results based on Eq. (2) for the model composite consisting of PTFE and AG-600 SO5 carbon filler (20 vol %) with the experimental pressure dependence of the linear wear rate for the wear of industrial F4K15M5 composite, in which the filler is foundry coke. For F4K15M5 composite, $a = 150 \times 10^{-15}$, $b = 515$, $c = 4 \times 10^{-14}$, and $d = 0.125$. Note that b is close to the b_1 value obtained from experimental data for the wear of PTFE at steel 45.

In Fig. 4, we plot the dependence of $I_{h\Sigma}$ on the pressure p when $v = 1$ m/s according to Eqs. (1) and (2) for F4K15M5 composite and the model composite. Curves *1* and *2* in Fig. 4 are close. The difference is due to the tribological properties of the foundry coke and AG-600 SO5 carbon and the discrepancy between the particle sizes r_p and r_f assumed for the industrial composite and their actual values.

Note that the satisfactory agreement of curves *1* and *2* in Fig. 4 validates the proposed approach to assessing the contributions of the filler and matrix to the total wear resistance of the composite. That allows us to predict the wear resistance of PTFE composites at the design stage on the basis of analytical formulas.

REFERENCES

1. Voronkov, B.D., *Podshipniki sukhogo treniya* (Dry-Friction Bearings), Leningrad: Mashinostroenie, 1979.
2. Bahadur, S., The development of transfer layers and their role in polymer tribology, *Wear*, 2000, vol. 245, no. 1–2, pp. 92–99.
3. Blancher, T.A. and Kennedy, F.E., Sliding wear mechanism of polytetrafluoroethylene (PTFE) and PTFE composites, *Wear,* 1992, vol. 153, no. 1, pp. 229–243.
4. Kong, D., Physical model of adhesive wear of PTFE, *Wear*, 1991, vol. 147, no. 1, pp. 9–24.

5. Tanaka, K. and Kawakami, S., Effect of various fillers on the friction and wear of polytetrafluoroethylene-based composites, *Wear*, 1982, vol. 79, no. 2, pp. 221–234.
6. Sedakova, E.B. and Kozyrev, Yu.P., Predicting the tribological properties of polymer composites on the basis of a physical model of wear, *Russ. Eng. Res.*, 2014, vol. 32, no. 2, pp. 76–78.
7. Kozyrev, Yu.P. and Sedakova, E.B., Influence of the structure of polytetrafluoroethylene-based composites on the stress in the matrix, *Probl. Mashinostr. Nadezh. Mash.*, 2010, no. 2, pp. 40–45.
8. Sedakova, E.B., Structure of tribological composites based on polytetrafluoroethylene with nanofiller, *Vopr. Materialov.*, 2013, no. 2, pp. 28–30.
9. Kozyrev, Yu.P. and Sedakova, E.B., Influence of the composition of carbon composites on their carrying capacity, *Russ. Eng. Res.*, 2008, vol. 28, no. 2, pp. 123–125.
10. Kozyrev, Yu.P. and Sedakova, E.B., Assessing the proportion of the load on the matrix in F4K15M5 polymer composite by comparing the dimensions of the wear particles, *Vopr. Materialov.*, 2011, no. 1, pp. 118–122.
11. *Spravochnik po plasticheskim massam* (Plastics Handbook), Kataev, V.M., Popov, V.A., and Sazhin, B.I., Eds., Moscow: Khimiya, 1985, vol. 1.
12. Russian patent 2 338 178.
13. Kragel'skii, I.V., Dobychin, N.N., and Kombalov, V.S., *Osnovy raschetov na trenie i iznos* (Fundamentals of Friction and Wear Calculations), Moscow: Mashinostroenie, 1977.
14. Berlin, A.A. and Vasin, V.E., *Osnovy adgezii polimerov* (Fundamentals of Polymer Adhesion), Moscow: Khimiya, 1969.

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