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Abstract

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ON THE ROLE OF FATIGUE PROCESSES IN THE ABRASION (WEAR) OF POLYMERIC MATERIALS

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1. The idea that wear is a process of surface fatigue failure ([1–3]) means that the separation of particles from the friction surface occurs not by a single act, but as the result of the gradual weakening of the surface layers subjected to repeated deformation during sliding. Verification of these ideas by comparing the wear resistance of a number of materials with their fatigue-resistance properties is unrealistic, since both these and other properties of a material depend strongly on the experimental conditions. Let us consider other approaches.

2. To compare wear with fatigue failure, it is necessary that wear occur without substantial scratching (microcutting). This condition is satisfied in the wear of sufficiently soft rubbers on a metal mesh—a surface with blunt protrusions ([9–11]). Further, it is necessary to find, on the one hand, a characteristic of wear that is specific to fatigue abrasion (and that has no significance in microcutting), and, on the other hand, a characteristic of fatigue failure of rubber that determines the intensity of its fatigue (and that has no significance in ordinary failure).

3. A characteristic specific to fatigue abrasion can be identified by comparing the laws of wear by sharp and blunt protrusions. It has been established that the influence of the load p on the wear intensity V of polymeric materials is determined by the formula

$$V = V_1 \left(\frac{p}{p_1} \right)^{\alpha}, \tag{1}$$

where V is the loss of height referred to the friction path; p_1 is the pressure taken as unity; V_1 is the wear at this pressure; α is a constant, substantially different from unity in abrasion by blunt protrusions ([5,9–11]), whereas in abrasion by sharp protrusions $\alpha \approx 1$ ([4–9]). It is therefore clear that, of the two characteristics—V_1 and α—it is precisely the quantity α that should be associated with

Fig. 1

Figure 1: Fig. 1

the corresponding characteristic of fatigue failure (since it appears only in wear by blunt protrusions).

Such a characteristic is the quantity δ in the formula describing ([3]) the Wöhler curve for the fatigue strength of rubbers

$$n = \left(\frac{\sigma_1}{\sigma_n}\right)^{\delta} = \frac{1}{K^{\delta}}, \tag{2}$$

where n is the number of cycles required for failure; σ_1 is the initial strength, and σ_n is the fatigue strength; K is the fatigue coefficient.

It is clear from the formula that the process of fatigue failure of a given material is characterized by the quantity δ, although the fatigue strength depends both on the initial (static) strength and also on the number of fatigue cycles ([12]).

Therefore, one should compare the change in the quantities α and δ when the composition of the material is changed. The quantity δ is the greater, the greater the number of cycles required for a decrease in strength (to a specified fraction K), i.e., the greater the forces

interactions in the material, which are gradually overcome during its fatigue fracture.

4. On the other hand, it has been established ([10,11]) that for a given series of rubbers α increases regularly with changes in their composition, corresponding to an increase in the forces of intermolecular interaction—when the polarity of the rubber or the activity of the filler increases, and plasticization or swelling decreases. It is therefore clear that, if wear is a fatigue process, then α and δ must correlate, changing in parallel.

From the data in Table 1 it is seen that such a correlation is indeed observed: changes in the composition of the material that lead to a change in δ also cause a sympathetic change in α. From Fig. 1 it is seen that

$$\alpha = \alpha_0 + \beta\delta \simeq \frac{1 + \frac{1}{2}\log n_{1/2}}{2}, \tag{3}$$

where $\alpha_0 = 0.5$; $\beta = 0.08 \pm 0.02$; $n_{1/2}$ is the value of n at $K = \frac{1}{2}$*.

Fig. 1. Comparison of changes in α and δ with change in the composition of rubber (from Table 1). 1—carbon-black-filled vulcanizates of butadiene-nitrile rubber; 2—unfilled vulcanizate SKN-26, swollen in T-1; 3—unfilled vulcanizate of polychloroprene, swollen in DBF

5. Let us compare these experimental results with theoretical relations. On the basis of fatigue concepts of wear ([15]), taking into account the theory of contact strength ([16]), I. V. Kragel' skii obtained

$$V \sim \frac{1}{n} = \left(\frac{\sigma_n}{\sigma_1}\right)^{\delta} \sim \left(\frac{\mu p}{\sigma_1}\right)^{\delta}; \tag{4}$$

$$V = C\mu^{\delta} p^{1+\beta\delta}, \tag{5}$$

where μ is the coefficient of friction; β is a constant determining the approach of the friction surfaces; C is a constant depending on σ_1 and the elastic modulus of the rubber. Comparison of formulas (1) and (5) gives formula (3), in which $\alpha_0 = 1,\ \beta = 0.14$. Earlier it had been obtained ([3]) that $\alpha_0 = \frac{2}{3},\ \beta = \frac{1}{3}$. These theoretical values of α_0 and β are close to those obtained by us from experiment (Fig. 1).

Table 1

Change in α and δ with changes in intermolecular forces

Material	Variable factor, %	α	δ	Source
Vulcanizate of butadiene-nitrile rubber, carbon-black-filled	Acrylonitrile fraction 0	1.1	10	Our data
Vulcanizate of butadiene-nitrile rubber, carbon-black-filled	Acrylonitrile fraction 18	1.3	22	Our data
Vulcanizate of butadiene-nitrile rubber, carbon-black-filled	Acrylonitrile fraction 26	2.6	35	Our data

Material	Variable factor, %	α	δ	Source
Vulcanizate of butadiene-nitrile rubber, carbon-black-filled	Acrylonitrile fraction 40	3.8	56	Our data
Same, unfilled	Same 0	1.0	3	α—our data; δ—from ([13]) for another rubber composition
Same, unfilled	Same 18	1.3	4	α—our data; δ—from ([13]) for another rubber composition
Same, unfilled	Same 26	1.9	6	α—our data; δ—from ([13]) for another rubber composition
Same, unfilled	Same 40	2.4	8	α—our data; δ—from ([13]) for another rubber composition
Vulcanizate SKN-26, unfilled	Swelling in T-1 0	1.9	14	δ—from ([14]); α—our data
Vulcanizate SKN-26, unfilled	Swelling in T-1 8.6	1.6	12	δ—from ([14]); α—our data

Fig. 2

Figure 2: Fig. 2

Material	Variable factor, %	α	δ	Source
Vulcanizate SKN-26, unfilled	Swelling in T-1 15.6	1.3	9	δ—from ([14]); α—our data
Same, polychloroprene	Swelling in DBF 0	1.8	19	Same
Same, polychloroprene	Swelling in DBF 4.3	1.6	16	Same
Same, polychloroprene	Swelling in DBF 15.2	1.3	12	Same

* Since the interaction forces exert a decisive influence on the initial strength and, consequently, also on V_1, there must be some correlation between α and V_1 (as also between δ and σ_1), which is indeed observed. Thus, for hundreds of rubbers of different composition there is a single relation:

$$V_1 \simeq \text{const} \cdot e^{-2\alpha} \sim n_{1/2}^{-0.2}.$$

6. Table 1 (and Fig. 1) give the values of δ obtained under static loading of different duration t (here t is analogous to n). For checking formula (5) this is immaterial, since the value of δ is almost the same under cyclic and static loading ([17,18]). However, taking into account the indifference of the value of δ to the type of fatigue fracture—cyclic or static—the correlation of α and δ still does not speak unambiguously about the role of repeated actions in wear, but only about the identical role of a prolonged action needed to overcome intermolecular forces, which increase the resistance to both surface fracture (abrasion) and bulk fracture (static and dynamic rupture).

Fig. 2. Comparison of the values of α and μ in wear without lubrication of various rubbers on a mesh.
1 —data from Table 2

Therefore, checking the role of friction is of special interest. It follows from formula (5) that a change in the coefficient of friction sharply affects wear, since the value of δ is substantially greater than 1. This result sheds light on one of the darkest points in the phenomenon of wear: the effective role of lubrication and

the large fluctuations in wear resistance with small changes in friction (Table 2). From the data in Table 2 it is seen that although lubrication of the swollen rubber led to a greater decrease in its coefficient of friction than lubrication of the unswollen rubber, the wear of the latter decreased more strongly than that of the swollen rubber ([5]). This is understandable, since for the swollen rubber α, and hence δ, is smaller than for the unswollen rubber.

Table 2

Effect of lubrication on the coefficient of friction and the relative value of wear of polymeric materials on a metal mesh

Material	Lubricant	α	μ	V
Carbon-black-filled rubber based on SKN-40	None	5	0.76	100
Carbon-black-filled rubber based on SKN-40	MK oil	–	0.30	0.4
Carbon-black-filled rubber based on SKN-40	Ratio	–	2.5	250
The same rubber, swollen by 22% in DBF	None	2	0.95	100
The same rubber, swollen by 22% in DBF	MK oil	–	0.29	1.5
The same rubber, swollen by 22% in DBF	Ratio	–	3.3	70

Material	Lubricant	α	μ	V
Unfilled rubber based on SKN-26	None	1.8	1.10	100
Unfilled rubber based on SKN-26	TsIATIM-221 lubricant	2.2	0.23	1
Unfilled rubber based on SKN-26	Ratio	–	4.3	100
Polystyrene	None	1.8	0.36	100
Polystyrene	Spindle oil	3.0	0.15	1
Polystyrene	Ratio	–	2.4	100
High-pressure polyethylene	None	1.3	0.5	100
High-pressure polyethylene	Spindle oil	2.0	0.2	4
High-pressure polyethylene	Ratio	–	2.5	25

Moreover, since a decrease in friction increases the number of cycles required for fracture during wear, and the latter varies symbatically with α,

then one should expect an increase of α as μ decreases. This is also seen from Table 2 both when estimating the role of lubrication and when comparing three rubbers worn without lubrication. A similar tendency is seen in Fig. 2.

7. Thus, the fatigue theory of wear explains the nature of the magnitude α and the regularities of wear of polymeric materials based on its role, established experimentally earlier ([5,9–11]). In analyzing formula (8), we used experimental data only for the abrasion of rubber on a metal mesh. But our conclusions have a more general character, since the wear characteristics of polymeric materials on a mesh (V_1 and α) correlate with analogous characteristics for wear on solid metal ([19–21]).

However, the wear of rubber by an abrasive (sandpaper, etc.) occurs mainly through microcutting, although, owing to the high elasticity of rubber, a certain

fraction of the material is separated after fatigue under repeated deformation. Therefore the total wear on sandpaper is usually hundreds of times more intense than on a mesh, while the fraction of fatigue wear on sandpaper is hundreds of times smaller than that of abrasive wear. Since $\alpha = 1$ in abrasive wear of any materials ([4]), in the wear of rubber on sandpaper α differs very little from unity.

Conversely, in wear not on a cutting surface, $\alpha > 1$ even for plastics ([9]), which indicates a substantial fraction of fatigue wear, increasing in the transition from sharp protrusions to blunt ones.

Thus, wear of polymeric materials may occur as a fatigue process, which provides a basis for seeking ways to increase wear resistance and fatigue strength simultaneously ([22]).

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Note: Figure translations are in progress. See original paper for figures.