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Figure 1

Figure 1: Figure 1

Abstract

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THE EFFECT OF TEMPERATURE ON THE WEAR RESISTANCE OF POLYMERIC MATERIALS

THE ROLE OF FORCED ELASTICITY

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It is well known that a change in temperature leads to sharp changes in the deformation and strength properties of polymers. Since wear, i.e., the destruction of a body at the friction surface, is determined above all by these simpler mechanical properties of the material, let us consider how wear resistance changes with temperature, proceeding from its effect on these properties of polymers ([1]).

Fig. 1. Schematic of the effect of temperature on the mechanical properties of amorphous polymers: σ —strength, ε —elongation at break ([5,9]), H —hardness ([6]), μ —coefficient of friction ([1,7,8]), V —wear ([1]). T_x —brittleness temperature, T_c —glass-transition temperature, T_t —flow temperature.

1. The relation of wear V to the simple mechanical properties of a polymer may be qualitatively represented by the ratio

$$V \sim \mu/H\sigma\varepsilon_m,$$

where V is the loss of height referred to the friction path. The role of the coefficient of friction μ is obvious. It is clear that wear resistance is greater the higher the hardness ([2]) H and the strength ([3]) σ. Less obvious is the role of the elongation at break ε_m, which has been shown quite recently ([1,4]). Meanwhile, for solving the problem we have posed, it is of great importance, since an increase in temperature, while reducing the strength and hardness of plastics, simultaneously increases their elasticity, i.e., their elongation at break. Temperature has little effect on H and σ of a glassy polymer ([5]), but a very strong effect on ε_m ([5]). Therefore an increase in temperature may lead to an increase in wear resistance, contrary to generally accepted views.

Fig. 2

Figure 2: Fig. 2

2. Let us first consider this question for amorphous polymers. They are characterized by four zones (Fig. 1), the boundaries between which are the well-known conditional "transition points" : T_{x} –brittleness temperature, T_{c} –glass-transition (softening) temperature, T_{t} –flow temperature. In zone I (the material is brittle), as temperature rises the strength falls, as a result of which wear increases, since H, μ, and ε_m change hardly at all. In zone II, H and μ are still almost unchanged, while the strength continues to fall. But, being forced-elastic, the material is capable of very large deformations. After a very sharp increase in ε_m has compensated the fall in H, a further rise in temperature should lead to a decrease in wear.

On transition to zone III, the material is in the highly elastic state: its strength continues to fall, its hardness has dropped very sharply, and the coefficient of friction has increased. Because of the fall in strength, ε_m also begins to decrease ([9]). Therefore wear increases sharply. Zone IV (the viscous-flow state) is of little interest from the standpoint of wear resistance.

3. To verify these ideas, experiments were carried out on a MAST-1 machine of the KT type ([10]). However, the friction unit was modified: a steel cone, rotating at a speed of several mm/sec, slid over the specimen.

plastics, forming a chamfer in the cylindrical recess. Wear was determined from the loss of weight per unit time.

For the experiments, organic glass—polymethyl methacrylate (PMMA)—was chosen, an amorphous plastic with a large range of forced elasticity and a value of T_c substantially above room temperature T_k. This made it possible to carry out experiments with heating. The results are given in Fig. 2. The physical picture (Fig. 1) is in agreement with experiment, and the harder organic glass is indeed more wear-resistant; being also more heat-resistant (see Table 1), it gives a pattern of extrema at a higher temperature.

Fig. 2. Effect of the temperature of organic glass on wear (1, 2) and friction (3, 4) (in arbitrary units); 1, 3 –grade No. 1; 2, 4 –grade No. 2.

4. A somewhat different picture is observed in the wear of fluoroplastic (Fig. 3) and other crystalline plastics, since the highly elastic state is not characteristic of them. Since their brittleness temperature lies far below T_k, these materials deform in a forced-elastic manner, and the wear corresponds to the region of a broad minimum. Therefore heating above T_k has almost no effect on their wear (it even decreases somewhat). Only on approaching the softening temperature T_p (melting temperature) does the wear rise sharply; this rise corresponds to the last branch of the curve V,

Fig. 3

Figure 3: Fig. 3

and not to the first branch, located in the region of very low temperatures.

Fig. 3. Effect of temperature on wear (1, 3) and friction (2) (arb. units): 1, 2 –polycarbonate; 3 –fluoroplastic 3.

Since, along with the crystalline component, these plastics also contain an amorphous component, the picture becomes somewhat more complicated. Many crystallizing plastics at first give the picture characteristic of amorphous plastics. Thus, when polypropylene is heated (Fig. 4), at first the wear increases and then decreases, as for amorphous plastics. But after the specimen was heated, its wear at room temperature decreased in comparison with the initial value, and repeated wear testing gave a picture characteristic of crystalline plastics (Fig. 3, curve 3). Curve 1 in Fig. 3 refers to the wear of amorphous (transparent) polycarbonate. However, as wear proceeded at elevated temperatures, crystallization of the specimen was observed (it became strongly cloudy).

5. The comparison of theoretical conclusions with experimental data was, of necessity, qualitative in character. For, first, the formula does not claim a strict quantitative relation of wear to μ, H, σ, ε. Secondly, H, σ, and ε can be determined only under conditions substantially different from the complex stressed state in which wear occurs. The same applies to the temperature limits of change in the properties of the polymer (T_x, T_c, T_t). Thirdly, the indicated temperatures

boundaries depend strongly on the loading regime, especially on the magnitude of the load, which affects the softening temperature T_p of various materials to different degrees ([11]). Therefore the values of T_c, determined as T_p according to Vink, differ from the values of T_M corresponding to the minimum wear value (see Table 1). The difference between T_p and T_M is especially large in the case of crystalline polymers, since for them T_p is more sensitive to load ([11]).

Table 1

Comparison of the softening temperatures T_p, minimum wear T_M, and friction jump T_μ for a number of plastics

Material	Hardness, kg/mm^2	T_μ	T_M	T_p	$T_p - T_M$
Organic glass No. 1	14	75	77	85	8
Organic glass No. 2	20	95	95	105	10

Fig. 4. Effect of temperature on the wear of polypropylene (1, 2) and on friction (3) (conventional units): 1—before warming; 2, 3—after warming

Figure 4: Fig. 4. Effect of temperature on the wear of polypropylene (1, 2) and on friction (3) (conventional units): 1—before warming; 2, 3—after warming

Material	Hardness, kg/mm^2	T_μ	T_M	T_p	$T_p - T_M$
Polycarbonate	14	75	75	155	80
Polypropylene	5	95	95	165	70

However, one may use the quantitative picture given by the effect of temperature on friction, since it is measured during the wear process. In Figs. 2 and 3 it is seen that in the region where wear decreases, friction does not change. This means that, in fact, the wear resistance increased not because of a decrease in friction, but because of a sharp increase in elongation at break, which more than compensated for the decrease in strength. Moreover, it is known ([1]) that when vitrified amorphous polymers are heated, the increase in friction begins only above T_c, as a result of the increase in contact area. And indeed (Table 1, Fig. 2), friction begins to rise in the range of temperatures corresponding to minimum wear, which, according to our ideas, corresponds to T_c (Fig. 1).

For crystalline plastics, owing to the absence of a highly elastic state, there is also no rise in the coefficient of friction upon heating. Heating leads ([1]) to a decrease in friction at the softening temperature (melting of the crystals). At the same time a sharp increase in wear is observed (although friction decreases), because hardness and strength fall very sharply.

Thus, the experiments have shown the validity of the concepts concerning the influence of temperature on wear in accordance with its influence on the simple mechanical properties, whose role in regulating wear resistance is described by the proposed formula. The experiments confirmed the special significance of the elasticity of polymers, expressed by their elongation at break, a sharp increase of which in the region of forced elasticity can cause an increase in wear resistance when the temperature is raised in the glassy state.

Fig. 4. Effect of temperature on the wear of polypropylene (1, 2) and on friction (3) (conventional units): 1—before warming; 2, 3—after warming.

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