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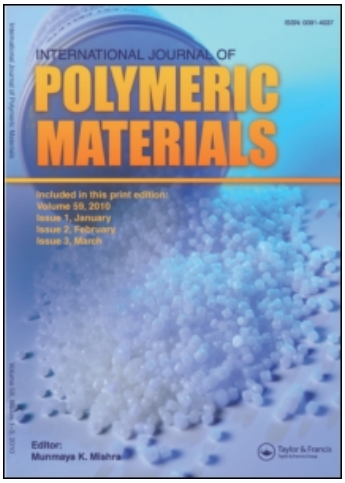

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The Effect of Anomalous Low Friction of Polymers by Bombing with Accelerated Helium Atoms

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New effect that is a drastic drop to anomalous low level (<0.002) of friction coefficient value in vacuum for steel-polymer friction pares is described. The effect was found by combing polyethylene and polypropylene surface with fast helium atoms simultaneously with friction process. The effect disappears spontaneously after irradiation is ended.

INTRODUCTION

In previous works[1,2] radiation effects on friction properties of polymers were studied only for cases when the whole volume of the specimen was exposed to radiation, i.e. when high-energy electrons or gamma-rays were used. Furthermore, radiation exposure preceded substantially the friction process studied. This resulted in considerable changes in both surface and volume properties of polymers. Besides, these changes had ample time to restore before the beginning of the experiments. In consequence, the study of the mechanism of radiation effect on friction presented a rather complex problem.

Great importance is therefore attached to external friction studies with one of the couple elements exposed to a flux of low-energy accelerated particles.[3] The method enables a combination of friction with a purely surface irradiation of the sliding solid in a sufficiently wide energy range, both the intensity of radiation and the depth of its penetration into the friction body being gradually adjustable. A variety of phenomena (free radical formation and recombination, bond destruction and connection, formation of gaseous radiolysis products, etc) may be induced in polymers by such an exposure, which

ultimately results in substantial changes in the friction behaviour of polymers. The changes observed are caused by purely surface effects.

THE SETUP AND THE EXPERIMENTAL PROCEDURE

The experimental device that was used to study the effect of fast atoms and molecules of some elements on friction properties of polymers is shown in Figure 1.[3]

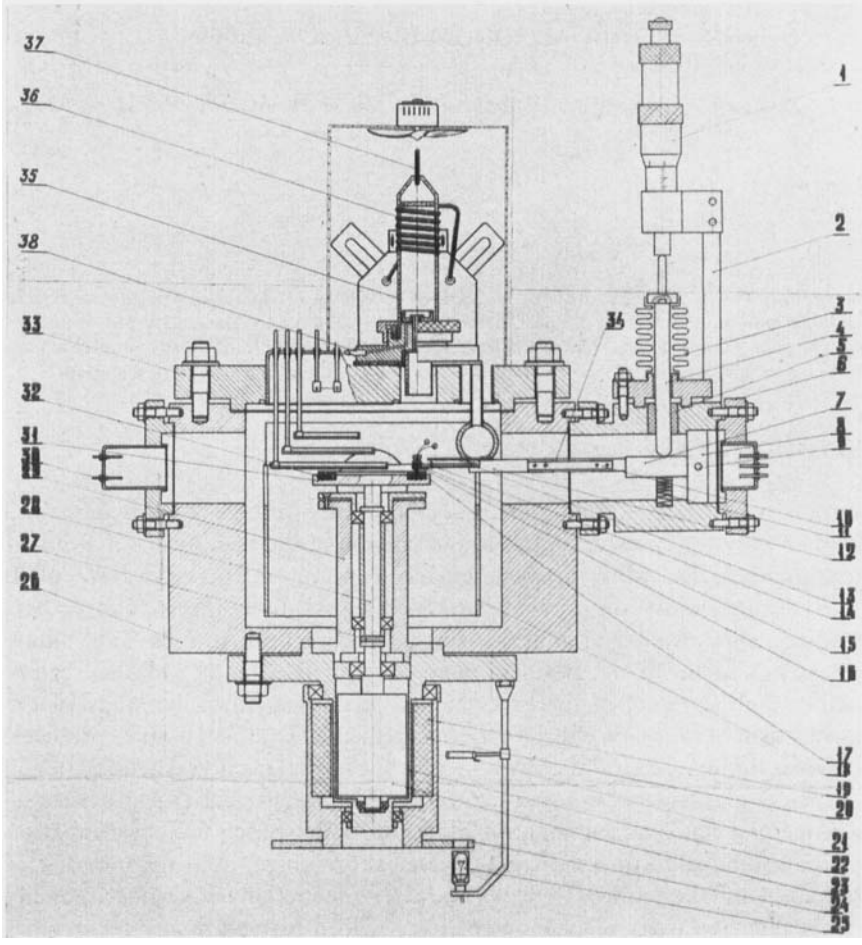

FIGURE 1 The general view of the experimental setup.

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The setup comprised a steel vacuum chamber (26) with a friction couple inside. The latter consisted of a rigidly fixed steel ball rider (17) (IIIX-15-type of steel) and a rotating polyethylene specimen (32) placed in a grooved metal disk.

The load was transmitted to the ball by a lever (7) fixed on the shaft (9). The loading system also comprised a micrometer (1) and a metal rod (4) with a bellows vacuum seal. The disk specimen was rotated in vacuum by means of a magnetic coupling. The rotation speed was recorded by a light tachometer connected to a recounting device. Strain gauges to measure loads and friction force were attached by an adhesive to measuring beams (12 and 13), two gauges at each side, and connected to a resistor to form a Wheatstone bridge actuating a recorder.

The vacuum chamber was connected to an electrical discharge high-vacuum oil-free pump with a pumping speed of 300 l/sec. The system comprised three nitrogen traps and a screen (18) located around the friction couple. The test specimens used were annular disks made of high-density polyethylene (PE), polypropylene (PP) and polytetrafluoroethylene (PTFE) with an outer diameter of 5.5 cm, an inner diameter of 4.0 cm, and a thickness of 0.5 cm.

A source of fast neutral atoms was provided by a glass chamber (35) having a sealed-in anode charged to +2200 V relative to the earth-connected enclosure of the device and to the accelerating tube (41), a cathode (40), a screen (39), and an ion collector.

A discharge at a gas pressure of 8×10^{-2} torr was generated in the glass chamber by a circuit (36) connected to a high-frequency generator. The cathode (40) was maintained at a voltage of +300 V. With the collector placed against the output tube, it was possible to measure the current of the accelerated ion flux with an energy of 2.2 kV; the current density obtained in the experiments was about 75 μa/cm^2. With the collector turned aside, the ion flux was directed onto the rotating polymer surface. Due to ion irradiation the polymer surface was rapidly charged to the value of the accelerating potential, the accelerated He^+ ions were resonantly recharged on neutral helium atoms to produce fast atoms of He, an appreciable amount of which could be detected in the tube output. Since considerable difficulties are involved in the measurement of fast neutral particles, only rough estimates of flux intensities will be presented here.

If the tube (41) where fast atoms of helium are recharged has a pressure of 8×10^{-2} torr at its output, a flux of accelerated ions of 75 μa/cm^2 at an output pressure of 10^{-5} torr will correspond to a fast atom flux of approximately 10^{14} atoms per second (calculated from a known recharge cross-section). From geometrical considerations the "spot" of the atomic beam on the polymer specimen must have a diameter of about 1 cm.

A point to be noted is that the real intensity might be somewhat lower due

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to dissipation effects that are not allowed for in the calculations. At the pressures indicated, however, one can hardly expect a high degree of atom dissipation. The effect of dissipation seems rather difficult to correct for. For temperature measurements in the contact area a thermocouple was used with a junction placed within the ball indentor at 0.03 cm from the sliding surface.

The specimens analyzed were thoroughly rinsed in carbon tetrachloride and alcohol and placed into a chamber that was subsequently evacuated to obtain a vacuum of 10^{-7} torr. The specimen was ground in in vacuum until stable friction at the working load and speed was reached, the temperature in the contact area ranging from 27 to 30°C. Then the ion pump was turned on and the rotating polymer surface was bombarded with neutral He atoms. Friction and temperature changes at a given speed and load in the contact area were also measured.

THE EXPERIMENTAL RESULTS

For the first few seconds of radiation exposure specimens of polyethylene (PE), polypropylene (PP) and polytetrafluoroethylene (PTFE) showed a marked increase in the friction coefficient (Figures 2 and 3). After further

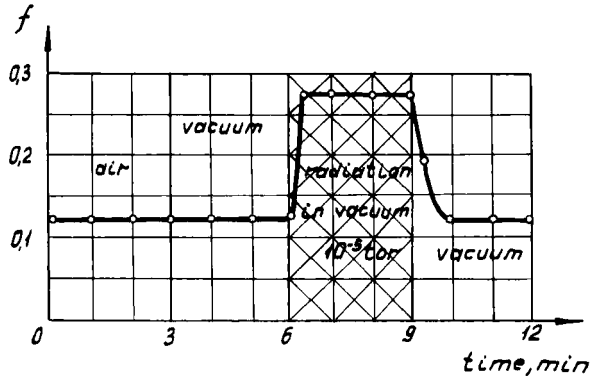

FIGURE 2 PTFE friction curve.

irradiation the friction coefficient of PE and PP specimens unexpectedly dropped down to about $\leqslant 0.002$, i.e. to the sensitivity limit of the device. The time taken by the friction coefficient to fall to such a low level varied from 70 to 100 sec and was reproduced in repeated experiments. No such effect was observed in PTFE specimens where high friction coefficients persisted through the whole period of radiation exposure. On switching off the radiation source, PTFE exhibited a relatively fast reduction of the friction force to its original

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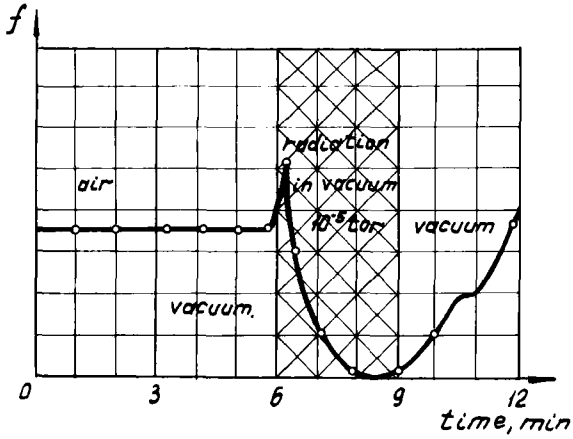

FIGURE 3 Polyethylene friction curve.

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value (Figure 2), while in PE and PP there was a gradual growth of friction that lasted for hundreds of seconds and could be divided into two stages (Figure 3).

During irradiation the temperature in the contact area of PE and PP specimens was some grades lower than in normal conditions. The effect of abnormally low friction was maintained at indentor loads of up to 350 g (which corresponded to a contact pressure of up to 250 kg/cm^2) and at sliding speeds of up to 600 cm/sec (both the values are maximum for the present device). By further investigating the mechanism of friction recovery in PE it was shown that while the first stage of the process could occur spontaneously, the second could not do without friction and was the faster the higher were the loads and sliding speeds.

The decisive role of neutral particles in the effect observed was confirmed by intercepting ions by means of a positively charged (+2200 V) grid (42) placed between the accelerating tube (41) and the polymer specimen (32). No change in the effect resulted.

Repeated experiments with the same and different specimens showed a good reproducibility of results. Polyethylene specimens had very smooth surfaces which can be taken as an indirect evidance of their negligibily small wear. It should be noted that if the vacuum in the chamber was broken, the effect disappeared immediately. Similar effects with somewhat different times of friction drop and restoration were obtained by exposing polyethylene specimens to fast particles extracted from a discharge in argon, hydrogen, nitrogen and air.

By using a mass-spectrometer to measure the chamber background while irradiating a polyethylene specimen, it was shown that a significant amount of radiolysis-induced hydrogen had been diffused from the polymer, the residual

diffusion detected corresponding to a flux of 2.5×10^{15} molecules/cm^2 sec at the moment of exposure termination and 2.2×10^{13} mol/cm^2 sec 100 seconds after the exposure.

It was also shown that to obtain the effect of abnormally low friction in a new polyethylene specimen the latter should undergo special training consisting in simultaneous friction and radiation exposure for 25 to 40 min in real experimental conditions.

It was finally established that some threshold intensity of radiation was necessary to obtain the low friction effect.

Examination of the irradiated sliding surface through an optical and electron microscope revealed a transformation of the surface from a relatively rough to a very smooth one with friction decreased to the abnormally low level.

DISCUSSION

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As is known, neutral helium atoms accelerated to the energy of 2 kev can penetrate into hydrocarbon polymers to some scores of Å[4] which is several orders of magnitude less that the mechanical indention depth of the ball slider in polymers in our experiments. Only surface properties of a polymer can be therefore affected by radiation exposure. The drastic fall of friction after such an exposure indicates that in the conditions studied friction properties of PE and PP are determined only by the surface interaction of the sliding materials.

From Bowden's equation[5] $F = A_r \tau_j$, where A_r is the actual contact area and τ_j is the adhesive bond shear strength, it follows that a change from the normal friction to an ultralow one is associated with at least two order of magnitude decrease in τ_j since A_r must remain unchanged due to to the constancy of polymer volume properties mentioned above. τ_j is in turn directly proportional to the polymer surface energy whose minimum permissible value is 10 erg/cm^2 which is only 2 to 3 times as low as its normal value for polyethylene.[5] Hence, the effect observed can not be explained in terms of Bowden's adhesion model of friction.

It also follows from the above that the effect discovered can be ascribed neither to electrostatic charge accumulation during friction, nor to the aerostatic pad effect, as, according to our estimates, the necessary amount of gas produced by the polymer should be some orders of magnitude higher than the maximum value of the diffusion hydrogen flux determined in our experiments.

The comparatively long recovery period shows that the above effect was not caused by radiation-induced electron or phonon excitation, since the phenomena in question have much shorter attenuation times.

On the other hand, such a long recovery period suggests that the factor

responsible for the effect is the formation of specific structures, which, besides being radiation-induced, are probably largely due to molecule orientation in the polymer surface layer during friction.

The structures may disappear more or less quickly after radiation exposure (PE, PP) or may persist for a long time and require a mechanical effort to be removed (PTFE). The properties and transformation kinetics of these structures may largely depend on the ambient gas, mostly oxygen. After such metastable structures disappear, the extremely smooth surface is gradually reduced by friction to its original roughness, and the friction coefficient is completely restored.

To furnish direct evidence for the existence of such structures more sophisticated techniques of investigating surface layers of polymers will have to be developed.

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