The Friction and Wear of Very High Molecular Weight Polyethylene

INTRODUCTION

The friction and wear behavior of irradiated polymers has been little studied. McLaren and Tabor[1] examined the frictional properties of poly(tetrafluoroethylene) (PTFE) which had been irradiated with γ-rays up to 50 Mrad. Except at the highest sliding speeds, it was found that irradiation increased the friction coefficient. Matsubara and Watanabe[2] studied the friction and wear behavior of high-density polyethylene (HDPE) after γ-irradiation. The friction coefficient increased up to a certain level of irradiation and then decreased. The wear behavior was complicated.

In the present work, the friction and wear of very high molecular weight polyethylene (VHMWPE) is reported.

EXPERIMENTAL

The polyethylene used was RCH1000. This is a linear polyethylene with a viscosity-average molecular weight of 1,250,000 as measured in decalin at 80°C. This is not quite in the ultrahigh molecular weight region, the lower limit of which is at about 1,500,000.

Samples were sliced from a rod of the material and had a thickness of 5 mm. Irradiation was carried out using a ^{60}Co source, with the samples under an argon atmosphere. Doses of 20, 50, 100, 200, 500, and 1000 Mrad were given. The color of the samples changed on irradiation, with the 20-Mrad sample a pink color, the 50-Mrad sample being a light brown, and succeeding samples having a darker coloration, the 1000-Mrad sample being a dark brown.

The samples were examined using x-ray diffraction methods to determine the crystallinity. Scans were made using a Norelco diffractometer, and the area under the scan was divided into crystalline and noncrystalline regions.

Infrared studies were carried out on samples microtomed from the 5-mm discs using a Perkin-Elmer Model 180 spectrometer.

Solubility studies were made in decalin at 150°C on microtomed samples using an antioxidant to minimize degradation.

Load–extension curves were obtained on an Instron testing machine, using type V ASTM standard test samples,[3] at a cross-head speed of 0.2 in./min. Microhardness measurements were made with a Vickers indentor. The load was 0.8 kg, and the time of application of the load was 30 sec.

Friction and wear behavior were studied using a thrust-washer wear testing machine.[4] The samples were milled flat and then polished in stages down to a final step in which 0.05 μ alumina was used. The counterface was 316L stainless steel which was polished in the same manner as the polyethylene samples. Friction coefficients were determined under a load of 5 lb (corresponding to 125 psi) at a speed of 25.6 ft/min. Under these conditions, surface heating resulted in a temperature increase of 25°C as measured by a thermocouple placed close beneath the surface of the polyethylene samples. Wear was measured for a range of loads keeping the speed constant at 25.6 ft/min. At each load, the wear was monitored as a function of time using a Dektak profilometer. A wear curve consisted of an initial wearing-in part followed by a part of lower slope in which the wear was proportional to the time. A wear factor may be derived from this slope and the data are presented as wear factors versus load.

RESULTS

The x-ray data (Table I) show that the crystallinity of the starting material is 52%. This is typical for a high molecular weight polyethylene, and the usual density is 0.93–0.94. The crystallinity decreases somewhat on irradiation.

TABLE I
Data for Irradiated VHMWPE Compared to the Starting Material

Irradiation dose, Mrad	Crystallinity, %	Solubility fraction	Yield stress, kg/mm²	Hardness, kg/mm²	Elongation to break, %	1/2 Yield stress/ hardness	Coefficient of friction
0	52	—	2.24	4.12	450	0.272	0.190
20	52	0.281	2.70	5.49	420	0.246	0.305
50	49	0.135	2.71	6.18	150	0.220	0.295
100	43	0.100	2.84	7.01	80	0.203	0.270
200	42	0.059	2.91	7.66	20	0.190	0.258
500	42	0.040	3.40	8.82	15	0.193	0.246
1000	38	0.031	3.64	13.62	10	0.134	0.209

The infrared scans show the presence of an absorption peak at 10.35 μ after irradiation corresponding to *trans* unsaturation. This peak increases in height with increased radiation dose.

Solubility values are given in Table I. The solubility decreases with increasing dose, indicating crosslinking.

The effect of irradiation is to increase the yield stress and to decrease the elongation to break. The tensile strength shows a decrease for low doses followed by an increase at higher doses. The hardness increases with irradiation (Table I). The friction coefficient increases on irradiation, with the highest friction coefficient for the 20-Mrad specimen. With increasing dose, the friction coefficients decrease from this maximum, as shown in Table I.

Figure 1 shows a graph of wear factor versus pressure for the 1000-Mrad sample. This graph is typical for the other irradiated samples. At low pressure, the wear is low but increases sharply at a critical pressure. However, further increase in the pressure again results in a low wear factor.

DISCUSSION

The effect of γ-irradiation of VHMWPE is to cause crosslinking with a concomitant decrease in crystallinity. This conclusion may be supported by the observation that the irradiated polymer shows rubbery behavior when heated above its melting point. Indentation experiments above the melting point reveal that the indentation is not permanent but is eliminated on removal of the indentor. The increase in crosslinking is also reflected in the increase in hardness and yield stress and the decrease in elongation to failure.

If it is assumed that the friction is due to an adhesion mechanism, then the friction coefficient is given as the ratio of the shear strength to the penetration hardness.[5] For many materials, the shear strength is about half the yield stress in tension.[6] In Table I, the ratio of one half the yield stress to the hardness is given. For the irradiated samples, there is a fair agreement between the calculated and measured friction coefficient. There are several reasons why the calculated values are lower. The measured coefficient may

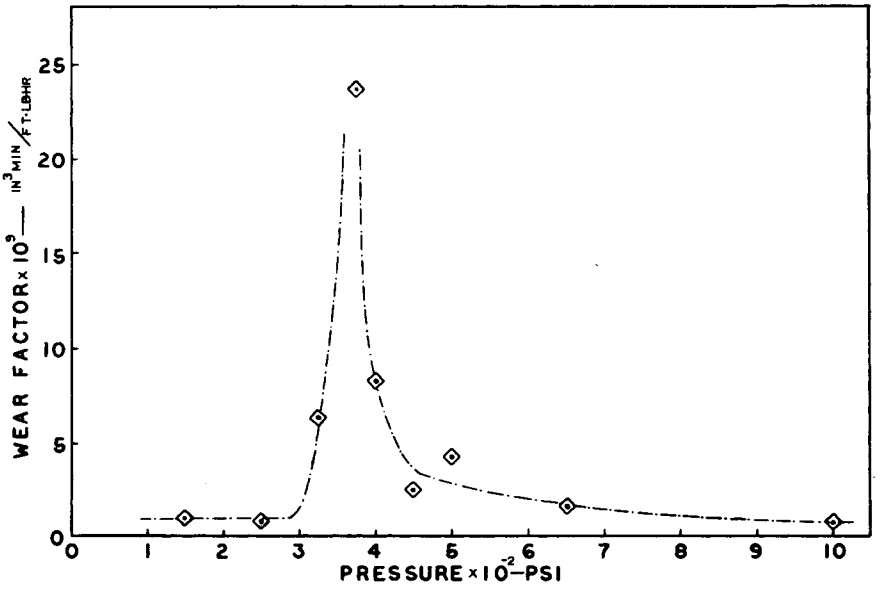

Fig. 1. Wear data for VHMWPE irradiated to 1000 Mrad.

be due to hysteresis as well as adhesion. The assumption that the shear strength is half the yield stress may not be exactly true. Furthermore, the identification of the friction coefficient with the ratio of the shear strength to the penetration hardness is only valid if the real area of contact is determined by plastic deformation. For a polymer, the deformation is likely to have a large elastic component. Lastly, the mechanical properties were measured at room temperature, while the properties should be determined at a temperature corresponding to the interfacial temperature on sliding.

The calculated friction coefficient does not agree with the measured coefficient for the unirradiated polymer. Pooley and Tabor[7] have found that the friction of PTFE and HDPE is influenced by transfer of polymer forming an oriented film on the counterface. The shear strength of this film is low, and hence the friction coefficient is lower than predicted from the bulk properties. This is why the calculated friction coefficient is too high. If crosslinking inhibits the formation of a transfer film, then the shear strength will be that of the bulk material, and this accounts for the agreement between the calculated and observed friction coefficients for the irradiated samples.

The wear behavior after irradiation is very interesting, and this behavior has not been reported heretofore. The response of the unirradiated polymer is that the wear factor is constant up to a critical pressure, at which pressure the wear factor increases substantially. Further increase in pressure leads to wear rates so high that the test has to be halted. This response is typical of most polymers. The increase in the wear rate corresponds to surface melting of the polymer due to the generation of frictional heat.[8] With the irradiated samples, the wear rate increases as for the unirradiated sample; but instead of melting, the polymer goes into the rubbery state and the wear rate decreases. Matsubara and Watanabe[2] noted that irradiated HDPE showed rubbery behavior for sliding under extreme conditions of pressure, but the behavior shown in Figure 1 was not reported. The hypothesis that the wear transition is connected with the generation of a critical surface temperature is supported by calculations of surface temperatures. These calculations and a more complete explanation of the phenomenon will be reported elsewhere.

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