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The Influence of Accelerated Electron Irradiation on the Change of Tribological Behavior of Polymeric Materials PET, PTFE & PE2000C

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The presented work deals with the study of the effect of increasing the doses of irradiation by accelerated electrons on the sliding properties of polymer materials. Due to the influence of radiation, surface roughness changes occur on the surface of the experimental materials, which lead to changes in the properties of the coefficient of friction on the selected polymer materials. Three types of polymer materials PET, PTFE and PE2000C were used for the experimental research, which, due to their properties, are used for different types of sliding products. A steel ball of G40 material was used as a pressure material, which moved along a linear path on which the load was increased from 10 N to 100 N. Electron beam accelerators with the conversion of electrons to X-rays combine the advantages of a high ability to penetrate gamma photons sources and high performance of electron beam devices. The application possibilities of the device are wide due to the dual mode of operation (electron beam or X-ray beam) and a wide range of applicable doses and also dose rates.

Keywords: Coefficient of friction, Polymers, Materials, Linear electron accelerator, Roughness

1 Introduction

Recently, polymer materials have been increasingly used in various branches of industry. The reason is their easy processing, low weight, resistance to corrosion and especially their affordability. In the application of polymer materials, these are often structural elements that require very good sliding properties (sliding bearings, sliding guides of chains and belts, etc.). Polymers have a lower coefficient of friction (COF) than e.g., ceramics or metals because their surface energy is lower. For this reason, some polymer materials can be applied to the production of structural parts, which are subject to increased demands for their frictional properties. Polymer materials with good dry sliding properties include mainly polytetrafluoroethylene (PTFE), polyoxymethylene (POM), polyamide (PA), ultra-high molecular weight polyethylene (UHMWPE), polyethylene terephthalate (PET), polybutylene terephthalate (PBT). The sliding properties of polymers can be positively influenced by adding antifriction additives such as graphite, MoS_2, Al_2O_3), liquid synthetic lubricants, polytetrafluoroethylene (PTFE) and various others. The sliding properties are influenced by a whole range of input factors, such as the used friction materials of the moving pair, the roughness of the surfaces, the specific pressure, the sliding speed and also, above all, the method of heat removal, which is generated in the friction process. The thermal conductivity of polymers is very low and increasing the temperature above the critical value increases their COF. The thermal conductivity of polymers can be increased by adding thermally conductive additives such as copper, graphite, carbon fibers etc. [1]. Polymers have specific properties that metals or ceramics do not, so their use is suitable for sliding contacts. They stand out thanks to good resistance to some chemicals, relatively low tendency to seizing, high temperature lubrication (PTFE), self-lubricating ability (PA) and low modulus of elasticity [1, 2].

Friction itself is defined as the resistance to relative movement arising between two bodies pressed against each other in the area of contact of their surfaces in the tangential direction [1-3]. In case of sliding friction, a force of resistance to relative motion arises, which is parallel to the direction of motion and is defined as the frictional force F_T. The value of the friction force is directly proportional to the value of the normal load F_N. Friction is evaluated using COF as a dimensionless quantity [4, 5]. COF is given by the ratio of the tangential frictional force to the load normal force ($\mu = F_T / F_N$).

An important role is also played by the possibility of improving their properties due to irradiation with accelerated electrons, which brings ordinary polymer materials closer to other, highly resistant materials with their newly acquired properties. Ionizing radiation is a type of electromagnetic radiation or

particles that have high enough energy to remove electrons from atoms or molecules exposed to this radiation, thus causing the formation of positive or negative ions [6]. According to the nature of the ionization process, ionizing radiation can be divided into directly ionizing and indirectly ionizing.

Directly ionizing is formed by charged particles (electrons, positrons, protons, α and β particles) that have sufficient kinetic energy to cause ionization. Indirectly ionizing is formed by uncharged particles (photons, neutrons). These particles do not ionize the environment, but when they interact with it, they release secondary, directly ionizing particles. Ionization is then caused by these secondary particles. [6]. According to the method of energy transfer, we divide ionizing radiation into wave and corpuscular. The wave propagates through space in the form of waves that transfer part of the energy from the source to the space. According to the behavior in an electric and magnetic field, we distinguish α radiation, β radiation and γ radiation (Fig. 1). The α radiation is formed by helium nuclei. Their energy is in the range of 4 MeV – 9 MeV. The particle has a very short range in the substance environment, because this heavy particle with two positive elementary charges strongly ionizes the substance, which slows it down. β-radiation is formed by fast electrons or positrons with a large energy range (up to 16.6 MeV). The range of β radiation with a maximum energy of 2 MeV in air is about 8 cm, in water 1 cm and in aluminum 4 mm (Fig. 2). γ-radiation is electromagnetic radiation with a very short wavelength (10^{-11} - 10^{-13} m), made up of photons - particles without a charge, which are distinguished only by their energy. It arises during nuclear reactions or radioactive decay by the transition of the nucleus from a higher to a lower energy state, when the nucleus gets rid of its excitation energy. The interaction of γ radiation with the material environment is significantly different from the interaction of electrically charged particles, and the range is much greater. When passing through the environment, photons release electrically charged particles and sell them additional energy to be able to ionize and excite the environment. Thus, γ radiation is indirectly ionizing radiation [6].

The base unit is Gray [Gy]. It represents the energy of one joule absorbed in a kilogram of substance. Radiation dose is the ratio of the average energy delivered by ionizing radiation to a substance of a certain mass.

The aim of the work is to determine the effect of irradiation with accelerated electrons on the friction properties of selected polymer materials depending on different doses of γ radiation. Due to the influence of radiation, surface texture changes occur on the surface of experimental materials, which lead to changes in the properties of the coefficient of friction on selected polymer materials. These changes are presented and analyzed in the present paper.

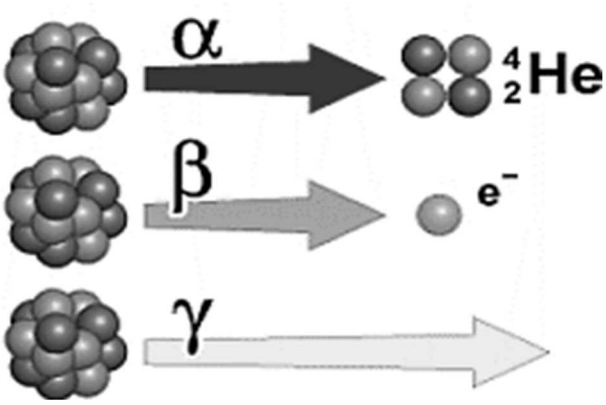

Fig. 1 *Types of ionizing radiation*

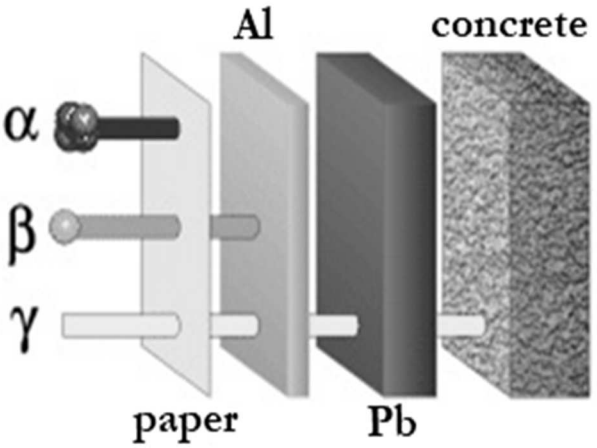

Fig. 2 *Radiation permeability of different types of materials*

2 Materials and methods

Samples of polymer materials provided by TechPlasty Žilina, s.r.o. were used for the experiment, namely PET – polyethylene terephthalate, PTFE – polytetrafluoroethylene and PE2000C – high molecular weight polyethylene modified with glass microspheres. Polyethylene terephthalate (PET) - is a thermoplastic with a semi-crystalline structure. It has very good mechanical and sliding properties, stiffness, hardness, wear resistance, excellent dimensional stability, and good electrical insulation properties. It is suitable for the production of precise, dimensionally constant loaded mechanical parts, wear-resistant structural elements, parts of food machinery, gears and pulleys, electrical insulators [7, 8]. The second experimental material polytetrafluoroethylene (PTFE) – is insoluble below the melting point (327 °C), nonflammable, has excellent electrical insulation, chemical, thermal, and sliding properties. It is used for sliding bushings and rails at high temperatures, parts of food machinery, seals, and O-rings for chemically aggressive environments [9, 10]. The last experimental

material is high-molecular polyethylene modified with glass beads (PE2000C). Due to its extremely high molecular weight, it is highly tough in a wide range of temperatures, does not undergo stress corrosion and above all has excellent sliding and wear-resistant properties, therefore it is suitable for use in highly wear-resistant sliding elements, paper machine parts, pump parts [11].

Tab. 1 *Selected mechanical and physical properties of experimental polymer materials*

Material	Specific weight [g/cm³]	Yield strength [MPa]	Bending strength [MPa]	Melting point [°C]	COF [-]
PET	1.38	80	125	255	0.25
PTFE	0.95	17	6	327	0.06
PE2000C	2.16	38	22	138	0.12

For the experiment, 24 pieces of samples with dimensions of 20 x 30 x 5 mm were made, while 8 pieces of test samples were made from each type of material.

The test samples were irradiated with a linear electron accelerator UELR-5-1S at the University Center for Electron Accelerators of the Slovak Medical University (UCEA SZU) in Trenčín. The UELR-5-1S accelerator (Fig. 3) is intended for the implementation of various radiation-technological processes and radiation sterilization, using a beam of accelerated electrons developed into a band, and also for the implementation of research works in various industrial areas [12].

Fig. 3 *Electron accelerator UELR-5-1S (left) and the irradiating room with a conveyor beneath the exit window in the ceiling (right)*

The test samples were irradiated with accelerated electrons with doses of 33 kGy, 129 kGy and 300 kGy and marked accordingly (Tab. 2). The principle of irradiation of material samples with accelerated electrons is shown in Fig. 4.

Tests of radiation dose values and subsequent control during routine irradiation are carried out using dosimeters made of radiochromic foils with the commercial designation B3 (GEX Corporation, USA). These dosimeters had to be prepared before the actual irradiation. Individual radiochromic dosimeters cut from a roll of foil are shown in Fig. 5. The intensity of staining depends nonlinearly on the size of the dose - the higher the dose, the more intense the staining. A colorless dosimeter is non-irradiated [13, 14].

Cut-out radiochromic B3 foils must be wrapped as soon as possible in a material that does not transmit visible light and UV radiation, or unpacked individual dosimeters must be stored as soon as possible after cutting under a material that does not transmit visible light and UV radiation until the moment of their application to the irradiated sample [15, 16].

Tab. 2 *Labeling of irradiated experimental samples*

Material	Radiation dose			
	standard (without irradiation)	33 kGy	129 kGy	300 kGy
PET	PET_0	PET_1	PET_2	PET_3
PTFE	$PTFE_0$	$PTFE_1$	$PTFE_2$	$PTFE_3$
PE2000C	PE_0	PE_1	PE_2	PE_3

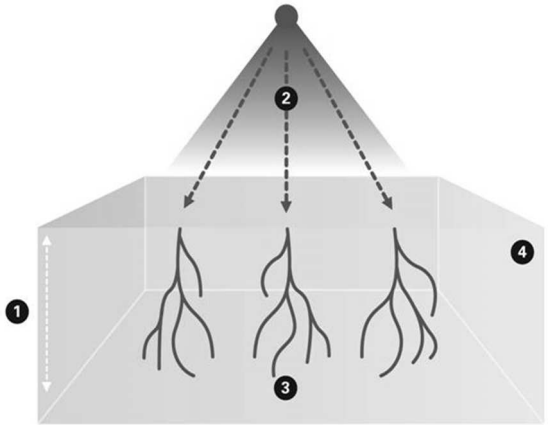

Fig. 4 *The principle of irradiation by accelerated electrons: 1 – depth of penetration of electrons; 2 – primary electrons; 3 – secondary electrons; 4 – irradiated material [12]*

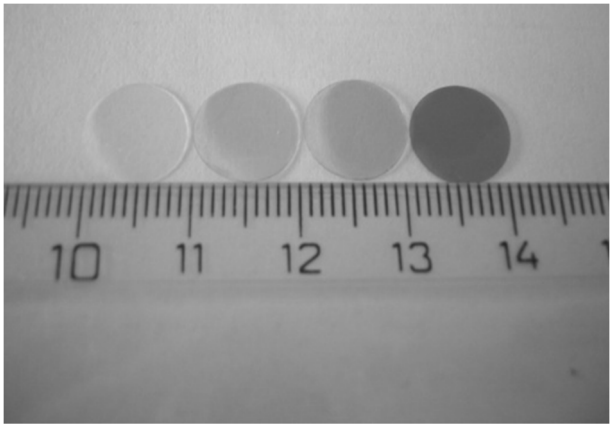

Fig. 5 *The B3 radiochromic films for routine dosimetry irradiated by different doses, the first one un-irradiated*

The universal tribologic testing device UMT TriboLAB was used to evaluate the sliding properties of the selected materials before and after irradiation (Fig. 6). Tests to determine the COF size were performed using the Ball-on-Flat method according to the ASTM-G133 Standard [17]. This method uses a measuring body in the form of a non-rotating ball that slides over a flat test specimen in a linear sliding motion. During the tribological measurement, the following parameters were set: an increasing linear load of 10 N - 100 N for 120 s on a measured path length of 20 mm without the use of lubricant. The contact pressure material was in the form of a ball of G40 material with a diameter of 4.73 mm.

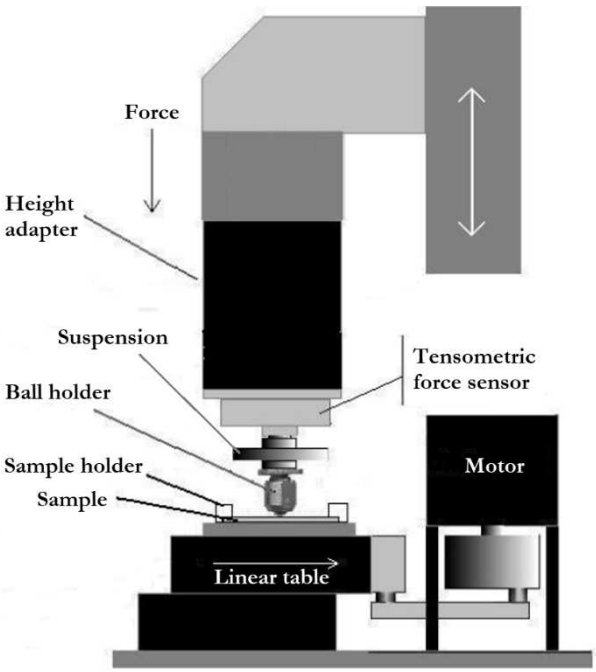

Fig. 6 *Schematic representation of the UMT TriboLab™ device*

As part of the evaluation of the irradiation rate and COF, surface roughness changes were also measured using an Olympus Lext OLS 5000 laser confocal microscope. A confocal microscope capable of capturing high-resolution 3D images of surface topography. It precisely measures surface shape and roughness at the submicron level. The magnification (optical and digital) of this microscope is in the range of 108x – 17.280x.

3 Results and discussion

After irradiation, the first evaluation of the change in roughness on all irradiated polymer materials followed. Figure 7 compares the roughness values of the PET material before and after all three doses of irradiation. The basic non-irradiated material reached a roughness Ra of 1.64 μm. Subsequent doses of radiation achieved a reduction in the roughness value Ra in all three results. The lowest roughness value Ra of 1.25 μm was achieved on the sample that was irradiated with a dose of 129 kGy. The second experimental material PTFE achieved a roughness Ra of 1.33 μm on the base sample. Irradiation with individual doses caused a decrease in roughness to the

lowest Ra value of 1.19 μm at a dose of 33 kGy (Fig. 8). Increasing the value of irradiation with a dose of 129 kGy caused the degradation of the surface texture in the form of an increase in roughness to a Ra value of 1.55 kGy. At the highest value of irradiation with a dose of 300 kGy, the roughness value decreased again. The last analyzed PE2000C sample reached a roughness value Ra of 2.11 μm on the base non-irradiated sample (Fig. 9). This highest roughness value of the basic experimental materials is due to the fact that the polymer material PE2000C is modified with glass microspheres. After the process of irradiation with individual doses, the roughness values increased after each dose and thus the degradation of the irradiated materials itself. The roughness results of all materials will later be compared with the sliding properties results and the conclusions and correlations of the given results will be evaluated.

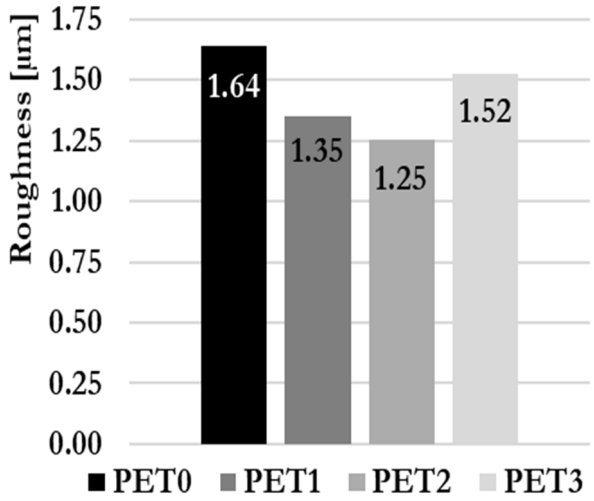

Fig. 7 *Comparison of roughness values for PET material samples*

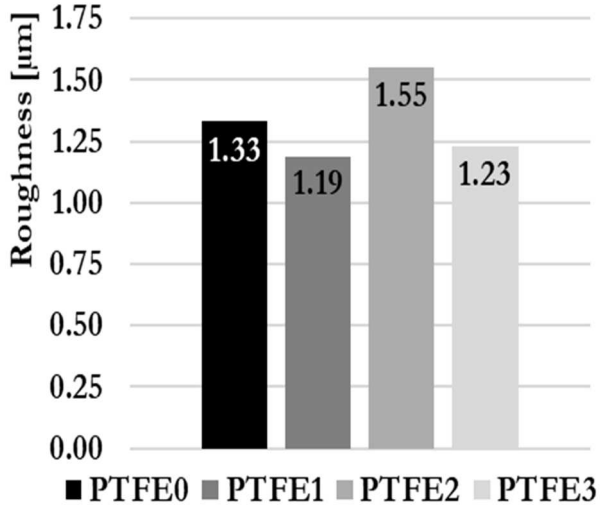

Fig. 8 *Comparison of roughness values for PTFE material samples*

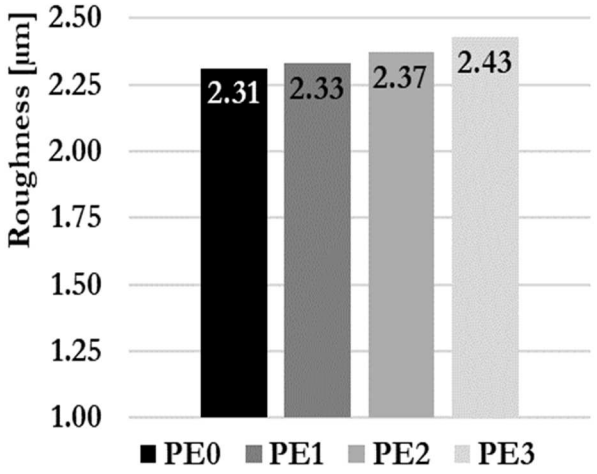

Fig. 9 *Comparison of roughness values for PE2000C material samples*

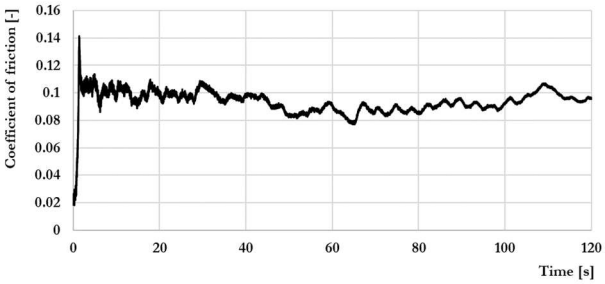

Fig. 10 *Coefficient of friction curve for sample PE_2*

The sliding properties of all samples were measured five times for statistical accuracy. As a result, the arithmetic mean of the COF values for all samples was evaluated and these means were subsequently analyzed. From a general point of view, the COF curve can be divided into three areas. The first time of the curve is formed by an almost linear part, which is characterized by the onset of frictional movement. The second part is formed by the peak, which creates the highest value of COF, which is caused by the rapid onset of the frictional force and its subsequent stabilization. The last third part of the curve represents the stabilization of the COF value, which can have a different direction character. All these three areas of the COF curve are observed on the COF curve of the experimental material sample PE_2, which we have chosen, which can be seen in Figure 10. In the given picture, in the third zone of the COF curve, I observe the stabilization of the COF value, which has an average value of 0.09. We also observe that this part of the curve consists of alternating values. The alternating values are caused by a combination of the friction process and the experimental materials used. Fluctuations in the values of the COF curve in the stable zone are caused by the accumulation and release of material, which is pushed in front of the pressure contact steel ball. The plastically deformed material in front of the ball is accumulated, and in the event of

accumulation of too much material, it is released and wraps around the edges of the friction track.

A comparison of all experimental polymer materials after irradiation with respect to the obtained COF values is shown in Fig. 11. The lowest COF value was achieved by the first experimental polymer material of the PET type. The latter also showed the lowest COF value of 0.042 on the sample without irradiation. By gradually increasing the radiation doses (33 kGy, 129 kGy), the COF value remained almost at the same value, while at the highest radiation rate of 300 kGy, the COF almost doubled to a value of 0.081. When comparing the preliminary results with the resulting roughness values of individual samples of PET material after irradiation, we can conclude that the radiation reduces the surface roughness, but by gradually increasing the doses of radiation, we degrade the experimental PET material. This degradation induced by the irradiated rays is significantly influenced by the radiation dose value, while at doses of 33 kGy and 129 kGy, the materials do not undergo such significant changes in sliding properties as at the highest radiation dose of 300 kGy.

The reference sample of the second experimental polymer material PTFE achieved the lowest COF value of 0.084 in the same way as the previous experimental material in the basic non-irradiated state. By gradually increasing the radiation doses, the COF values also increased. Comparison of the results of roughness and radiation doses for the experimental material PTFE are again closely related. At the first radiation dose of 33 kGy, the roughness also slightly decreased to the Ra value of 1.19 μm (Fig. 8) and, as with the previous material where there was a slight decrease in roughness, the COF remained almost at the same value when compared to the non-irradiated reference material PTFE. Increasing the radiation dose by 129 kGy led to an increase in roughness above the standard value, and here we can observe the synergy of the results for the COF value, which was the highest, namely 0.098. At the highest radiation dose of 300 kGy, the same COF value was achieved. But the roughness at the radiation dose of 300 kGy had a decreasing character. So, it can be concluded that if we used even higher doses of radiation than 300 kGy, the COF values would already have a decreasing tendency.

The last experimental material PE2000C and its non-irradiated sample again showed the lowest COF rate and had a value of 0.075. This investigated material, when comparing the COF results, replicates the roughness results (Fig. 9) after irradiation, which showed an almost linear increasing character. Since this material also achieved the highest roughness values on the last sample that was irradiated with a dose of 300 kGy, it also achieved the highest COF value of all investigated polymer materials, namely 0.113.

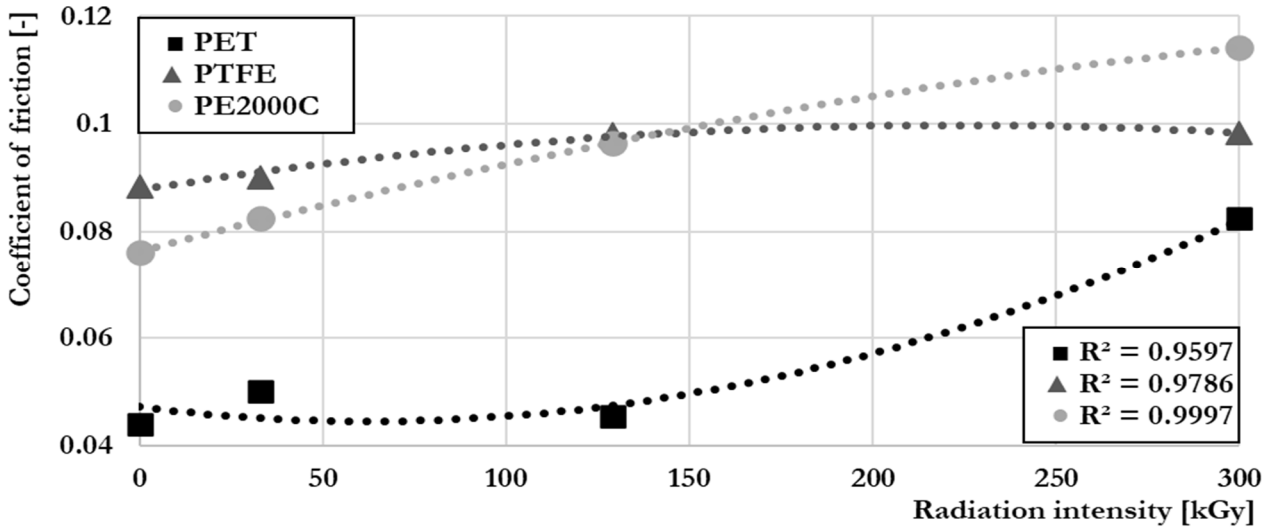

Fig. 11 *Comparison of the regression dependence of COF and radiation intensity for all experimental materials*

Figure 11 shows the quadratic regression dependence of COF depending on the radiation doses (33 kGy, 129 kGy and 300 kGy) for each experimental material. For the sample calculation, we chose the material PE2000C, where the given graph shows that with the increasing value of the radiation, the value of the friction coefficient will gradually increase. Considering the quadratic dependence and the shape of the parabola, we find the maximum value of ≈ 500 kGy of irradiation using the derivative of the regression function. After this value, the coefficient of friction will continue to increase. We determined this radiation dose value by using the first derivative of the obtained quadratic dependence. The calculation of the quadratic dependence for PE2000C material is shown in equation (1) with the calculation of the first derivative of the obtained quadratic dependence in equation (2):

$$y = -2 \cdot 10^{-7} \cdot x^2 + 0{,}0002x + 0{,}0763 \quad (1)$$

$$y' = -4 \cdot 10^{-7} \cdot x + 0{,}0002 = 0 \quad \Rightarrow \quad x = \frac{-0{,}0002}{-4 \cdot 10^{-7}} = 500 \quad (2)$$

The coefficient of determination R^2 was also evaluated, which for the material PE2000C has a value of 99.97%, which is a very high dependence between the input and output quantities. For the PET material, the graph shows that with increasing radiation value, the value of the coefficient will first decrease and then gradually increase. The value decreases only after irradiation with a dose of ≈ 57 kGy. We determined this radiation dose value by using the first derivative of the obtained quadratic dependence. The coefficient of determination has a value of 95.97%. For the material PTFE, it follows from the graph that with the increasing value of the radiation, the value of the coefficient of friction will also increase, up to a value of ≈ 250 kGy, after which the values of the coefficient of friction will have a decreasing tendency. The coefficient of determination has a value of 97.86%, which is again a high dependence between the input and output quantities.

4 Conclusions

The presented article deals with the effect of irradiation with accelerated electrons on the change of COF. The polymer materials PET, PTFE and PE2000C were used for the experiment, which were irradiated with three doses of 33 kGy, 129 kGy and 300 kGy. The samples were irradiated with a linear electron accelerator UELR-5-1. The entire experiment took place in a dry state on a 20 mm track with a linear increase in load from 10 to 100 N. In this evaluation, the authors also focused on the change in surface roughness of the experimental samples after irradiation. The following conclusions can be drawn from the presented work:

- The investigated experimental polymer materials are suitable materials that achieve a very low coefficient of friction in the range of 0.04 and 0.1 in the basic irradiated state.
- Irradiation of experimental materials leads, depending on the type of polymer material, to different surface roughness values in view of the radiation dose.
- PET polymer material reduces roughness under the influence of radiation at all three doses of radiation 33 kGy, 129 kGy, 300 kGy.
- Increasing radiation doses for the polymer material PE2000C leads to an almost linear increase in roughness from the basic value of the non-irradiated sample Ra 2.31 to the value Ra 2.43 for the last most irradiated sample with a dose of 300 kGy.
- The value of the coefficients of friction correlates with the obtained roughness results, which play the most important role in the resulting COF values.
- Irradiation with a dose of 300 kGy leads to degradation of the surface of the material with respect to the COF, which reaches the highest COF values for all experimental polymer materials at this radiation dose.
- By applying a regression analysis using a quadratic dependence, it was found that the values of the coefficient of friction increase or decrease with increasing radiation dose for the types of materials investigated.

In conclusion, we can state that already small values of radiation doses lead to a slight increase in COF values, but they are almost negligible. With the gradual increase in radiation doses, the COF values also increase, but their increase is influenced by the type of polymer material used. Irradiation therefore leads to the degradation of the material, which increases the resistance to friction and thus reduces the service life of the sliding parts that are made of these polymer materials. As a recommendation for the future, it would be interesting to use even higher radiation doses than 300 kGy for an in-depth analysis in which direction (linear, exponential) COF values increase.

Acknowledgement

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