THE INFLUENCE OF GAMMA-IRRADIATION AND HEAT TREATMENT ON WEAR OF UHMWPE AGAINST Co-Cr-Mo ALLOY IN UN-LUBRICATED CONDITIONS

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Abstract: The effect of γ-radiation and subsequent thermal treatment on the wear resistance and friction behavior of ultrahigh molecular weight polyethylene (UHMWPE) has been studied. Irradiation of the polymer was performed using a ^{60}Co γ-emitter at laboratory temperature. Radiation dose 50 kGy at the dose-rate 2.5 kGy/hr under a nitrogen atmosphere was applied. Some irradiated samples were thermally treated at 150 ˚C for a period of 30 min and then slowly cooled to the room temperature. A linear reciprocating pin-on-flat tribometer was used to investigate the wear behavior of UHMWPE (GUR1020) against a Cobalt Chromium Molybdenum (Co-Cr-Mo) alloy. The applied load of 100 N and motion frequency of 1 Hz were the test conditions for periods of 100 hr (equal to 69 km linear sliding distance). The tests were preformed in un-lubrication conditions in insulated surroundings (23±3 ˚C). An important increase in the wear resistance of the modified UHMWPE up to 68 % in comparison with the original material was proved. Besides the wear rate, selected mechanical characteristics (friction coefficient, Young's modulus, yield strength, fracture strength, and hardness) of the original and modified samples of UHMWPE were determined.

Keywords: gamma-radiation; thermal treatment; UHMWPE; wear resistance; mechanical property; dry conditions

Introduction

Ultra-high molecular weight polyethylene (UHMWPE) has been widely used as good material for total joint replacements (TJRs). The restricting factor of the use of UHMWPE is its wear resistance, and therefore wear remains a serious clinical problem [1-4]. According to the results obtained from experimental studies, the wear resistance of UHMWPE can be improved by one of the most applications of ionizing radiation (gamma-rays or accelerated electrons) if carried out under suitable conditions. Further increased its structural integrity, which translated into an increased lifetime of artificial implants is described in studies [5-7]. The mechanical properties of UHMWPE have been reported [7-9]. Thermal treatment (re-melting) subsequent to irradiation of UHMWPE is to recombine the residual free radicals generated during irradiation, and makes possible to re-arrange supramolecular structure of UHMWPE. These changes lead to an increase of degree of cross-linking and finally to higher wear resistance [7,10]. Lisa A. Pruitt [11] showed that a study of the mechanical properties plays an important role in determination the long-term success of orthopedic devices. On the other hand, Rizwan et al. [12] pointed out that consolidation of UHMWPE powder is improved by increasing of processing temperature with hot static pressing. This procedure, however, does not improve the wear behavior. Makoto Ohta et al [13] used slight cross-linked UHMWPE induced at a 5-kGy dose under reduced pressure at room temperature before compression what resulted in improvement of wear properties. The polymer becomes highly cross-linked after an absorbed dose of 50 kGy [14]. Table 1 shows some variables used irradiation that induces cross-linking UHMWPE subsequent thermal treatment. The influence of irradiation dosages on the wear properties has been reported for many types of UHMWPE (e.g GUR 4150 used in the USA and GUR 1050 used in Europe [15]) applied in TJRs. The thermal treatment step was used to increase chain mobility what enhances recombination reactions between the residual free radicals and so it increases the cross-linking [7-16].

Table 1: Variables used in radiation (rad) induced cross-linking UHMWPE [7]

rad. agent	Package medium	rad dose (kGy)	Post cross-linking details
γ	Air	45-1000	- Heated in air to 150 ˚C at 0.3 ˚C/min held at 150 ˚C for 5 hr slowly cooled to room temperature.
γ	N_2	50	- Re-melted at 155 ˚C for 24 hr

Cobalt Chromium Molybdenum (Co-Cr-Mo) alloy and UHMWPE have been used as the bearing material in TJRs for a long time. The bearing couples have a low friction coefficient and a good history of wear resistance, in spite of the fact that wear is still represents and cause a serious problem [17]. Sinnett-Jounes et al. [18] reported that Co-Cr-Mo alloys has superior tribological properties to titanium when used in TJRs. Dian et al. [19] concluded that the wear rate of

UHMWPE against CoCr was lower than that against titanium, while the friction coefficient were not significant for both. However, the wear rate in dry conditions was lower than in distilled water, while the friction coefficients were higher. This work studied the effect of irradiation and thermal treatment on the mechanical properties of UHMWPE (GUR 1020), and also the wear behavior and friction using severe conditions and a different wear test technique, and may be took consider as an initial impression a simulation wear test for TJRs.

Materials and methods

Sample preparation: The material used for the wear test was CHRULEN UHMWPE (GUR 1020) (Hi Poly Solidur, Germany), with an average molecular weight of $3.5x10^6$ g/mol. A counterface was used in the wear test, made from cobalt chromium molybdenum alloy (Co-Cr-Mo) with the standard specifications used in medical devices according to ASTM F-75. The wear sample and the counterface were machined by Walter Company, Czech Republic. The UHMWPE material was cut into two groups, discs-shaped 20 mm in diameters and 8 mm in thickness was the first group. The second group is dog-bones shaped samples specified to the tensile test. The counterface was machined in a determined shape, as shown in Fig. 1, and polished with average surface roughness (Ra=0.02) before testing. The procedure for cleaning the samples before the test was followed the standard guidelines given in [20]. The surface hardness was measured using Vicker's method (MHv= 9335 MPa)

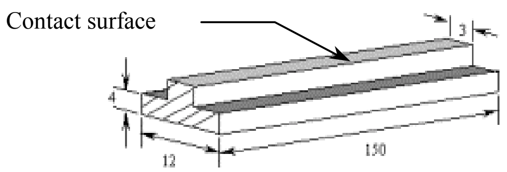

Figure 1: Dimensions of the counterface of Co-Cr-Mo alloy in mm

Irradiation and thermal treatment: some of UHMWPE samples were irradiated using ^{60}Co γ-rays (Nuclear Research Institute, Czech Republic) under reduced pressure at room temperature. The radiation dose was 50 kGy at the dose rate 2.5 kGy/hr in a nitrogen atmosphere. A thermal treatment was performed for some of the UHMWPE samples at 150 ˚C for a period of 30 min and then slowly cooled to room temperature.

Mechanical Properties: In this study, tensile tests were conducted at a constant cross-head speed of 50 mm/min at room temperature up to fracture. These tests were carried out on original (Or), irradiated (Irrd), and thermally treated (re-melting) (RM) samples of UHMWPE to find the effect of both irradiation and thermal treatment on the mechanical properties. The output test results were determined form stress-strain dependence. Three samples were tested for each condition and the standard deviations were determined for all measured properties, as shown in Table 2.

Wear tester: Linear reciprocating pin-on-flat tribometer was used to carry out linear sliding tests, as shown in Figure 2-a. Each test in this study was run for 100 hr with a frequency of 1 Hz and the sliding stroke was 75 mm. The applied normal load was 100 N (equal to 1.67 MPa contact stress of the UHMWPE sample). All tests were carried out at room temperature (21±2 ˚C) in dry conditions. Figure 2-b is a three-dimensional view of the position of the UHMWPE sample and the counterface. The interface temperature of the sliding parts during the test was measured.

Cleaning Process: Prior to wear testing, careful cleaning of the UHMWPE samples was important in order to remove any contaminants that would not normally be present on actual prosthesis parts. A standard guide was used in order to perform the cleaning process for the UHMWPE samples [20]. Each sample was cleaned by rinsing it under a stream of de-ionized water, then cleaned in an ultrasonic cleaner for 10-15 minutes in de-ionized water. Then it was dried using a jet of nitrogen. However, the counterface of Co-Cr-Mo alloy was used ultra sonically cleaned in de-ionized water for about 20-25 minutes then dried by a jet of nitrogen before wear testing.

Friction coefficient measurement: In the testing process, the moment generated by friction will be equivalent to the moment generated by the linear sliding of the sample holder. Therefore, a strain gauge was used to measure the friction coefficient. The output signal from the stain gauge was calibrated to the tangential force. The sliding friction coefficient was measured using a piezoelectric tensometer Kistler system with accuracy of 10^{-4} % of length variance.

Wear factor: The wear test results are shown by two wear factors, which is a function of the material property and applied test conditions defined as:

$$K = W_{ad} H / F_n \qquad [21]$$

$$K' = V/L * F_n \qquad [22]$$

Where K is the wear factor (mm/km), W_{ad} (mm^3/km) is the adhesive wear rate equal volume loss (V) per unit sliding distance (L), H is the material hardness, and F_n (100 N) is the normal load. The weight loss of the UHMWPE samples was measured using microbalance to an accuracy of 0.01 mg. The UHMWPE volume loss can be calculated by dividing the mass loss by the density of each group. The sliding distance is approximately equal to (69 km). The effect of radiation and thermal treatment on both the wear factor and the sliding friction coefficient is discussed in this paper.

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Table 2: Physical and mechanical properties of the original, irradiated and re-melted UHMWPE samples

	UHMWPE (GUR 1020)*			
	Or	Irrd	Or/RM	Irrd/RM
Density (g/cm^3)	0.9398	0.9463	0.9336	0.934
Tensile strength at yield (MPa)	21.92±0.18	23.13±0.75	18.67±0.34	19.49±0.65
Tensile strength at break (MPa)	27.54±0.15	28.00±0.7	18.06±0.46	20.52±1.45
Modulus of elasticity (MPa)	433 ± 9	545 ± 25	361 ± 17	415 ± 25
Elongation at break	321 ± 2	326 ± 22	294 ± 4	354 ± 11
Hardness (HB)	230	220	230	207

* (Or) = Original , (Irrd) = Irradiated , (Or/RM) = Original Re-Melted, and (Irrd/RM) = Irradiated Re-Melted

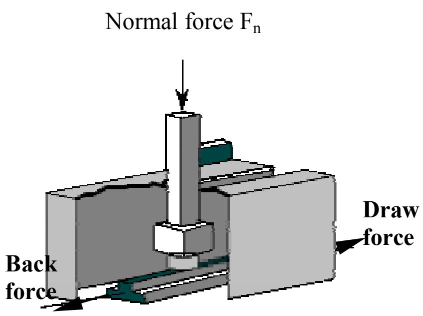

Figure 2-b

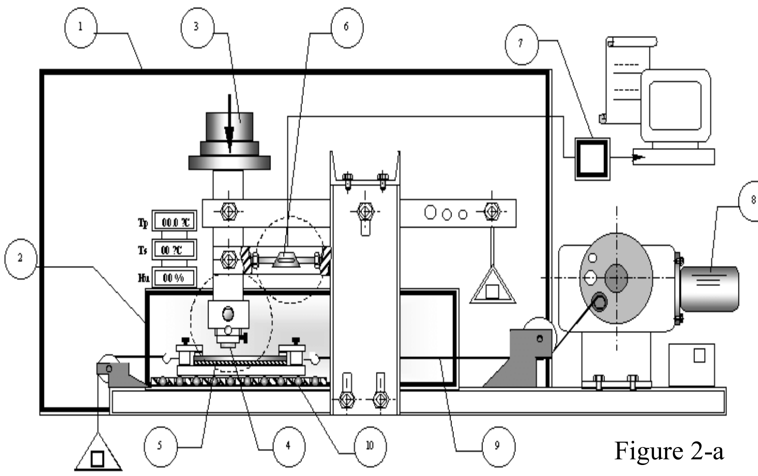

Figure 2-a

Figure 2: a) Schematic diagram (Linear reciprocating pin-on-flat apparatus): 1- outer cover; 2- inner cover; 3- applied weight. 4- UHMWPE sample; 5- sliding counterface; 6- strain gauge; 7- frictional force gauge; 8- electrical motor; 9- steel wire; and 10- bearing plate. b) 3-D view inside the inner cover indicates the applied forces

Results

Weight loss: the wear test of UHMWPE (GUR 1020) with Co-Cr-Mo alloy was studied in terms of the loss of weight and the time of sliding, Figure 3. The amounts of wear of the UHMWPE (original, irradiated, and re-melted) samples after 100 hr of sliding time (about 69 km of linear sliding distance) was evaluated as shown in Figure 4.

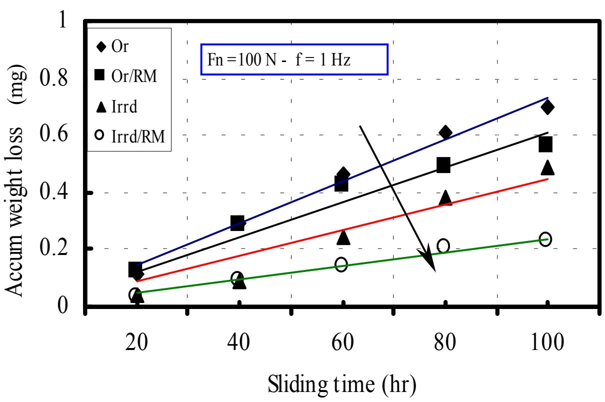

Figure 3: Relationship between weight loss and time of sliding at room temperature and (Ra = 0.02)

Wear factor: Figure 5 a, b show the wear factors (K) and (K') of UHMWPE (GUR 1020) sliding linearity on a flat surface of Co-Cr-Mo alloy with constant Ra (0.02). They have been used to realize the range of material hardness effect on the wear behavior of the UHMWPE.

Friction measurements: the mean of the friction between the sliding parts was calculated during the wear test in dry sliding conditions according to the normal applied load 100 N and frequency 1 Hz at room temperature

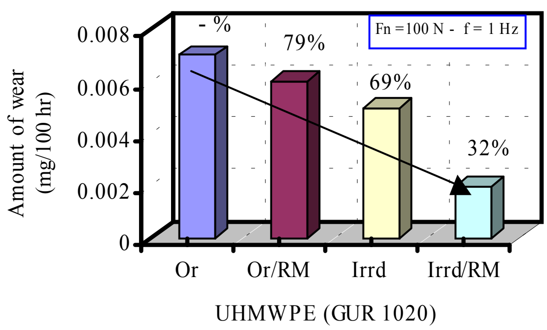

Figure 4: Comparison between the amounts of wear after 100 hr

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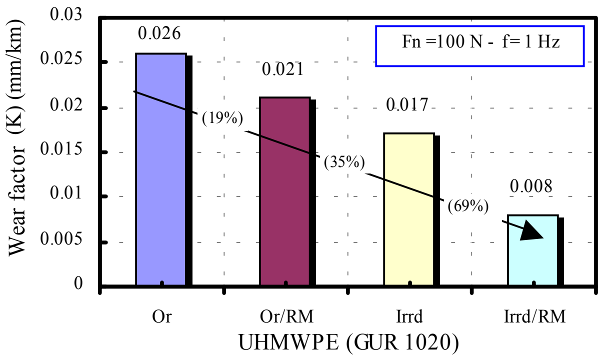

Figure 5-a: The effect of irradiation and thermal treatment on the wear factor (K) of the UHMWPE

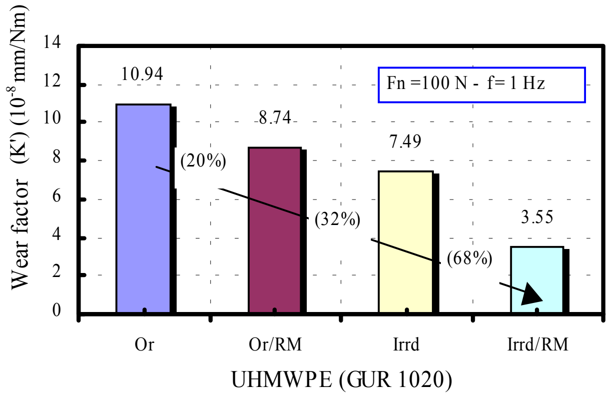

Figure 5-b: The effect of irradiation and thermal treatment on the wear factor (K') of the UHMWPE

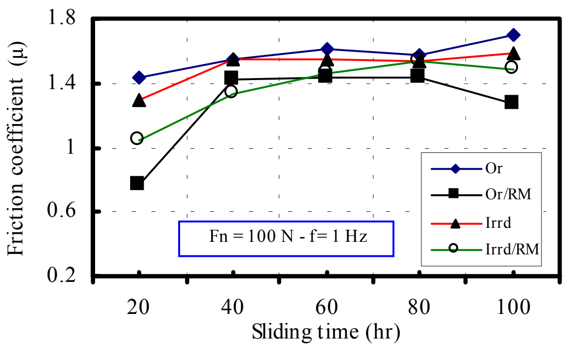

Figure 6: Variations in the friction coefficient with the sliding time in dry sliding conditions

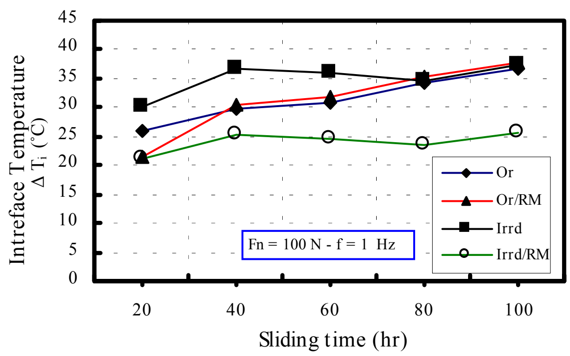

Figure 7: Variations in the interface temperature of UHMWPE and the counterface with sliding time

Discussion

Mechanical properties: Table 2 contains the mean values and standard deviation for yield tensile strength and tensile strength at break, elastic modulus, and elongation at break for the original, irradiated, and re-melted UHMWPE (GUR 1020) samples. It can be seen that an insignificant increase in both the tensile strength at yield and fracture and the elongation at break after the irradiation effect.

The modulus of elasticity increased by 25 % compare with the original sample. There is an obvious decrease in the properties after the re-melting process except in the case of the irradiated and subsequently re-melted (Irrd/RM) samples where the elongations at break increased. The hardness measurement shows that no more changes in the material hardness except that (Irrd/RM) sample has decreased and no significant changes were observed in the UHMWPE densities, Table 2.

Wear measurements: the relationship of the weight loss of the wear samples and the sliding time is shown in Figure 3. The amount of wear of the irradiated and subsequently re-melted (Irrd/RM) was lowest after 100 hr testing (about 69 km sliding distance) as shown in Figure 4. Gamma radiation subsequent heated treatment induced cross-linking in the UHMWPE that caused a reduction in the amount of wear by 32 % in comparison to the amount of wear of the original (Or) sample. It can be observed that the effect of only thermal treatment (Or/RM) itself? and irradiation (Irrd) on the amount wear are about 79 % and 69 % respectively.

Wear factor: the wear factors (K) and (K') have been determined to the tested material function of material properties such as material hardness, adhesive wear rate, and the applied load Equation (1, 2). These relations were used in order to study effect of the hardness on the wear resistance. Figure 5-a, b show variations the wear factors (K) and (K') with the original and the modified material. In comparison of each other cases it can be observed that the hardness of the material does not significantly affect on the wear behavior. The wear factors for all test materials were closed in the percentage, they were minimized at (Irrd/RM) sample.

Friction behavior: the 100 hr sliding friction of UHMWPE (Or, Or/RM, Irrd, and Irrd/RM) samples with constant surface roughness (Ra = 0.02) is shown in, Figure 6. The friction coefficients were having an irregular behavior than the wear results. The average of friction coefficient was highest for the UHMWPE (Or)

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samples (μ = 1.5) and lowest for the UHMWPE (Irrd) sample (μ = 1.4). The average friction coefficient is nearly in a steady state between 40 hr and 80 hr sliding test. The high increase in the friction coefficients were normally that resulted from the dry sliding conditions of the test, which are higher than they used lubricated conditions. The changes in the surface roughness of the counterface Co-Cr-Mo against all of the UHMWPE samples were not significantly change after testing time (100 hr). Only, there were slight linear scratches on the counterface surface.

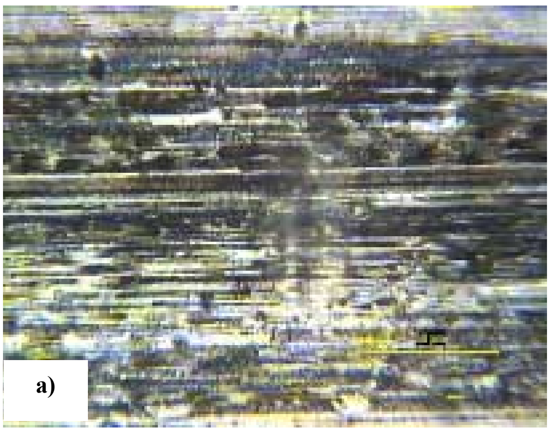
In Figure 7, is shown the increase in the interface temperature between the UHMWPE sample and the counterface during the sliding test was 40 ˚C about the room temperature. This is resulted from the sliding friction and not use a lubrication material, as well as the applied load and the long period of the sliding time. Some burnt debris were observed on the counterface surface, which may have led to an increase the sliding friction coefficient. It will be cleared in the microscopic analyses in the next paragraph.

Microscopic analyses: Two microphotographs, Figure 8-a, b show the UHMWPE (original and irradiated) debris on the counterface surface as a result of wear testing. It can be seen that the particles debris adhered on the counterface due to the applied and sliding force, which became as even layers on the counterface surface. Also, some of debris from the original sample changed to a black color that may have been due to an increase in the interface temperature about 40 ˚C between the sample and counterface caused an increase in the friction coefficient, Figure 8-a. The debris from the irradiated sample seem smaller than the original sample as shown in Figure 8-b. No significantly differences were found in the other cases of (Or/RM and Irrd/RM).

Conclusion

This study is an examination of the selected properties of UHMWPE, which was modified by application of gamma rays and subsequent heat treatment. The study was to (i) proof positive modification effect on wear resistance of UHMWPE used for artificial joints, and, (ii) determine how its other important end-use properties are influenced by this process. Significant effect of the modification steps on all the measured characteristics has been found.

1- The mechanical properties of UHMWPE were affected by the gamma radiation and thermal treatment (re-melting).
2- The wear behavior of the irradiated and subsequently re-melted UHMWPE (Irrd/RM) sample was found the best one. The effect of gamma radiation (50 kGy) and heat treatment (150 C for ½ hr) (Irrd/RM) increased the wear resistance up to 68 % compared with the original sample (Or).
3- The wear factors (K) and (K') as function of the material property (hardness), adhesive wear rate, and the applied load (100N) and sliding distance (69 km) was determined. The lowest value of the wear factors was also for the UHMWPE (Irrd/RM) although the hardness was lowest, therefore there is no significantly effect of the hardness on the wear behavior.
4- The friction coefficients were normally high in conditions un-lubricated. The average of the friction coefficient were approximately 1.4 to 1.5. There were no significant changes in the surface roughness of the counterface of Co-Cr-Mo alloy were found.
5- The interface temperature between the UHMWPE samples and the counterface were measured during the wear test. The temperature increased by up to 40 ˚C perhaps due to the increasing in the sliding friction that led to burn some debris of UHMWPE on the surfaces of the sliding parts.



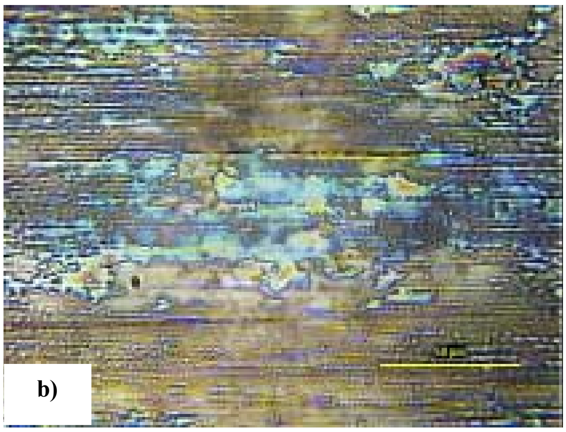


Figure 8: Microphotograph of the counterface surfaces after wear testing a) some wear debris form the original UHMWPE (Or), and b) from the irradiated UHMWPE (Irrd).

Acknowledgment

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