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Characterization of ultra-high-molecular-weight polyethylene (UHMWPE) modified by ion implantation

A. Valenza[a,*], A.M. Visco[a], L. Torrisi[b], N. Campo[a]

[a]*Dipartimento di Chimica Industriale ed Ingegneria dei Materiali, Università di Messina, Salita Sperone 31, 98166 S.Agata di Messina, Italy*
[b]*Dipartimento di Fisica, Università di Messina, Salita Sperone 31, 98166 S.Agata di Messina, Italy*

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Abstract

Surface modification of ultra high molecular weight polyethylene (UHMWPE) is induced by ion implantation of different ions at 300 keV energy. The aim of this work was the chemical, physical and mechanical characterization of the modified material in order to know deep inside about the effect of the ion beam upon the polymer.

The irradiated surfaces are investigated by Raman spectroscopy, infrared absorption and micro-hardness analysis, scanning electron microscopy. Pin on disc measurements valuated the wear of the UHMWPE against a stainless steel probe; wear resistance increases of about 76% after the ion implantation. This result can be attributed to the ion bombardment inducing a micro-hardness increasing in the irradiated layers due to the high carbon surface concentration and cross-linking effects in the polymeric chains. The irradiated UHMWPE surfaces may find special applications to the field of the mobile prosthesis.

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Keywords: UHMWPE; Ion implantation; Characterization

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1. Introduction

UHMWPE ($-\mathrm{CH_2}-|_n$ monomer) is an interesting polymer useful in different fields such as medicine, engineering, microelectronics and biology. A special application of this polymer in medicine concerns the interface of mobile joints, such as hip and knee prostheses, where the friction can be significantly reduced using intermeddled sheets of polyethylene [1]. The metal acetabular cup, for example, is generally covered by a UHMWPE sheet, in order to reduce the friction with the artificial femoral head. However, the wear of UHMWPE and the resultant wear debris inducing osteolysis is now recognized as one of the major causes of premature failure of the total joint replacement [2,3].

The hip and knee prosthesis must bear stress values that range from the body weight, under condition of slight movement, up to four or five times higher, under condition of quick movement. Thus the articulated joint implies that the surfaces in contact and in motion between each other are subject to remarkable sliding friction. A person weighing 60 Kg can transmit to the femoral head a maximum force of 2600 N. The time length of a walk cycle is assumed to be of about 1 s for a normal step. Each femoral head receives from 1 to 2.5 million impacts in one year. The velocity of slipping of surfaces on one another is about 0.05 m/s. The rotation range for a normal step is 45° due to flexion–extension, 12° due to abduction–adduction, and 14° due to internal–external rotation [4].

Recent literature reports many data about the wear improvement by using surface treatments of the polyethylene, which modify only the surface properties reinforcing its structure without change the bulk properties. The ion implantation, for example, can be applied with success to improve the surface hardness, to reduce the wear and the corrosion [5,6].

Generally, the irradiation of polyethylene with ionizing radiations induces de-hydrogenation and carbon enrichment. The ion bombardment, for example, modifies strongly the polymer chains especially along the ion track. The resulting irradiated polymer shows a surface layer rich of cross-linked ‘graphite-like’ structure with special tribological properties [7].

In this work authors discuss a possible surface modification

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[*] Corresponding author. Tel.: +39-90-393134; fax: +39-90-391518.
E-mail address: valenza@ingegneria.unime.it (A. Valenza).

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Table 1
Physic properties of the investigated materials

Material	Young modulus [9] (GPa)	Compression strength (MPa)	Friction coeff. metal-polymer [11]	Weight loss after 16 h (μg)	Hardness (Shore)
C hard graphite	4.8	360	0.1	0.233	100
UHMWPE	1.0	250	0.15	0.974	70
Irradiated UHMWPE (Xe^+, $3 \times 10^{15}/cm^2$)	1.0–4.8	250–360	0.1–0.15	0.232	90

method, the ion implantation, performed by using ions of different type and energy, at high doses, to induce graphite-like surface structures in UHMWPE. Results of wear tests, before and after the treatment, are presented and discussed. They show that the ion implantation method improves the mechanical resistance of the polymeric surface.

2. Experimental details

2.1. Materials

The UHMWPE sheet used in this work was Hoechst supplied, as white powder with sub-micron size. The density and the average molecular weight, quoted by the manufacture, are 0.930 g/cm^3 and about 10^6 g/mol, respectively. UHMWPE sheet, of about 5 mm thickness, was prepared by compression molding in a laboratory press. The polymer was kept at 180 °C for about 8 min at 200 bar pressure. The sheets were then pressed with a glass sheet at 180 °C for about 4 min at 10 bar to reduce the surface roughness at average values lower than 100 nm.

A graphite sample, employed as a standard, was Goodfellow supplied. The standard has a purity of 99.9% and it shape is 100 cm^2 surface and 10 mm thickness; its surface roughness was lower than 1 μm.

The point probe used for wear test was commercial stainless steel (AISI 316L); its point diameter was about 100 μm.

Table 1 shows some physical properties of some of the investigated materials.

2.2. Ion implantation

UHMWPE was implanted by using H^+, He^+, Ar^+ and Xe^+ ion beams having 300 KeV energy. The irradiation was performed using an ion flux ranging between 10^{14} and 10^{17} ions/cm^2 at the ion implantation accelerator of the Physic Department of Catania University. The current density was about 1 μA/cm^2 and the spot 1 cm^2. During the implantation the pressure inside the chamber was of 10^{-7} Torr and the temperature was 22 °C (room temperature).

The TRIM computation program of Ziegler and Biersack (version 2000) [8] was employed to calculate the ion ranges and the ion stopping powers in the UHMWPE targets. Table 2 reports these data for the different employed ion beams.

It can be observed that the range of penetration decreases with increasing ion mass, while the total (nuclear and electronic) stopping power increases with it. For this reason, the xenon ion is the best for a strong surface modification at relatively low doses, while hydrogen is the best for a deep modification but high doses are required.

2.3. Mass quadrupole spectrometry

A mass quadrupole spectrometer (MQS—Balzers, Prisma-200) was employed to detect, at high sensitivity, the partial pressure in the irradiation chamber. The mass range was 1–200 amu and the mass resolution better than 1 amu. The sensitivity, by using the SEM detector configuration of the MQS, was 10^{-14} Torr for argon mass. The MQS was employed for in situ analysis to detect the mass species emitted during the polyethylene ion irradiation [9].

2.4. Wear testing

The wear testing of pure and ion irradiated UHMWPE samples were performed on a 'pin on disc' test machine schematized in Fig. 1a and reported in the photo of Fig. 1b. A polymeric sample was placed on the rotating plate with a stationary stainless steel pin placed in friction on its surface. The wear tests were performed moving cyclically the metallic pin, subject to a fixed load, on the polymeric disc. The metallic probe point has a diameter of about 200 μm. The rotating plate speed was 0.074 m/s and the maximum contact pin pressure of about 25.5 MPa.

The maximum contact pressure (σ_{max}) of a stainless steel probe on an UHMWPE plan was calculated by following the

Table 2
Trim analysis and MQS data

Ion beam	Ion dose (ions/cm^2)	Range (μm)	Stopping power (keV/μm)	H_2-MQS yield
300 keV, H^+	5×10^{12}	3.8	62	0.75
150 keV, H^+	5×10^{12}	1.8	90	1.05
300 keV, He^+	5×10^{12}	1.9	250	2.8
150 keV, He^+	5×10^{12}	1.25	193	2.2
300 keV, Ar^+	1×10^{12}	0.46	669	2.3
300 keV Xe^+	6×10^{11}	0.2	1743	2.8

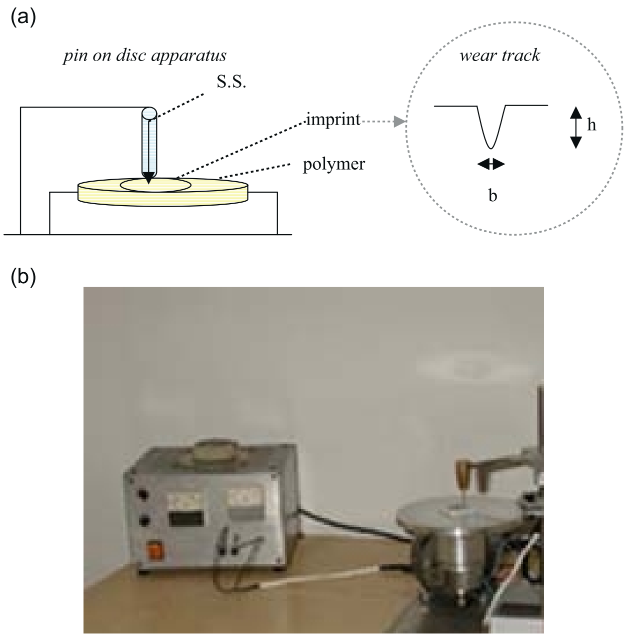


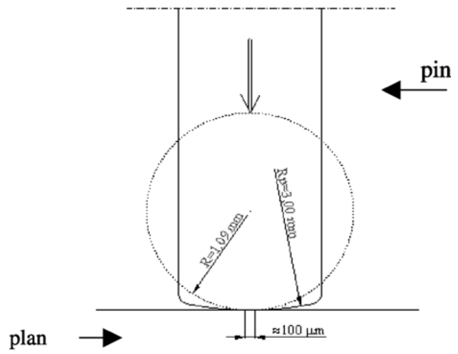
Fig. 1. Schematic of the wear track and of the wear test (a) and experimental pin on disc apparatus for wear resistance measurements (b).

equation of the Hertz theory [10]:

$$\sigma_{\max} = 1.5P/\pi q^2 \tag{1}$$

where q is:

$$q = [3/8P(\theta_1 + \theta_2)/\rho]^{1/3} \tag{2}$$



The stainless steel pin was assumed to have a spherical shape (over outlined in the picture). θ_1 is a factor which considers a Poisson index of 0.3 and a Young modulus of 210 GPa for the stainless steel pin and θ_2 is a factor which considers a Poisson index of 0.4 and a Young modulus of 1200 MPa for the UHMWPE plan. P is the metallic pin weight and ρ is the $2/r_1$ ratio, being $r_1 = 1.09$ mm the curving ray sphere-plan of the metallic pin.

The values of these factors are, respectively: $\theta_1 = 1.73 \times 10^{-5}$ (mm^2/N), $\theta_2 = 2.8 \times 10^{-3}$ (mm^2/N), $P = 0.05$ N and $\rho = 1.85$ mm^{-1}.

The pin-on-disk test is used as wear machine in order to evaluate the weight loss of friction material [11]. The weight loss, Y, was calculated from the measure of the depth (h) and width (b) of the wear track that have an approximate triangular profile (scheme presented in the insert of Fig. 1a):

$$Y = bh\rho\pi r \tag{3}$$

where ρ is the polymer density and $r = 1.175$ cm is the radius of the circle pin track. Giving h and b in cm units, Eq. (1) will give Y in grams.

The duration of the tests was varied between 1 and 4320 min.

Wear measurements were generally carried out at room temperature (22 °C). To evaluate the materials behavior at the body temperature (37 °C) and, generally, the temperature effect on the wear, the tests were repeated varying the polymer temperature in a range between 10 and 70 °C. All wear measurements were performed in dry conditions, without lubrication liquids.

2.5. Characterization techniques

2.5.1. Wear track

The wear parameters were determined with a Profiler Tencor-P10. The profiler moves a point along a single direction and the scansion is assisted 'on line' by an optical microscope.

Generally, the measurements were performed by using a tip force of 1 mg, a scansion length of 1 mm, and a scan speed of 100 μm/s. Measurements were performed at different places of the same wear imprint and average values were calculated.

2.5.2. Micro-hardness measurements

The micro-hardness measurements were carried out at room temperature with the Profiler described above. This instrument was employed with two different tip forces, one higher (50 mg weight) to cause a stress pressure imprint on the polymer surface and the other lighter (1 mg weight) to analyze the imprint profile. The imprint was obtained both statically and dynamically with a sweep of 10 μm length and a scan speed of 1 μm/s. The profile was recorded using 50 μm scansion length and 10 μm/s scan speed.

Since is known that hardness value of a pure UHMWPE sample is 70 Shore [12], it was possible to calculate the relative shore hardness of all the irradiated samples by comparing the difference in deepness observed with the profilometer.

The Shore scale is relative to the polymer hardness. If the probe tip full penetrates the polymer, the shore value will be zero (minimum value), while if the probe tips don't penetrate the polymer the shore value will be 100 (maximum value), as suggested from the Shore Hardness Testing (ASTM D 2240). Since the graphite isn't a polymer, its hardness scale should be measured in another scale (for example Vickers scale); anyway in this work we attributed to the graphite the maximum values of the Shore scale in order to compare the hardness of high density graphite with that of polyethylene.

Table 3
Main ATR transmission peaks

Sample	Wave number (cm^{-1})	Remarks
Pure UHMWPE	720, 730	C–H bending
	1462, 1473	C–H bending
	2847, 2915	C–H stretching
Irradiated UHMWPE (H^+, $10^{17}/cm^2$)	1647, 1669	C–C stretching
Pure graphite	1632, 1660	C–C stretching

2.5.3. Infrared spectroscopy

The transmission infrared spectra were registered with a Perkin Elmer Spectrum 2000 instrument equipped with a MCT detector. Two hundred scans were accumulated in the 4000–400 cm^{-1} wave-number region for each studied sample. The major ATR bands of the pure and hydrogen implanted samples are listed in Table 3 such Refs. [13,14].

2.5.4. Scanning electron microscopy

Scanning electron microscopy (SEM) was carried out with a Jeol JSM 5600 LU microscope. The samples were coated in vacuum with a very thin gold film to make them electrically conductive. The analysis was performed with employing a secondary electrons detector (SEI) to investigate the surface morphology of the pure and of the ion irradiated samples. Generally, the acceleration used voltage was of 10 kV. Generally, the photo magnification was 350.

2.5.5. Raman spectroscopy

A Raman microprobe analysis was employed to investigate the carbon content and the structure in the pristine polymer and in the ion irradiated polymer. The used spectroscope uses a Olympus B × 41 microscope having an objective lens of magnification 100. The Raman spectra are stimulated by a laser light at 632.8 nm and are detected through a reticulate of 1800 lines (HR 460, ISA-JobinYvon-595 ×) with a slit aperture of 0.1 mm.

For UHMWPE sample irradiated at high dose special attention was devoted to the investigation of the G-line at 1595 cm^{-1} and D-line at 1350 cm^{-1} wave numbers, typical for graphite-like structures. The G-line is attributed to the graphite structure formation in the material and the D-line to amorphous structure or ‘disorder’ in the material rich in carbon content [15].

3. Results

3.1. Chemical and physical surface characterization

Ion implantation modifies significantly the polymer surface. This phenomenon can be observed with several surface characterization techniques, such as the MQA spectrometry, the ATR and Raman spectroscopies and the SEM microscopy.

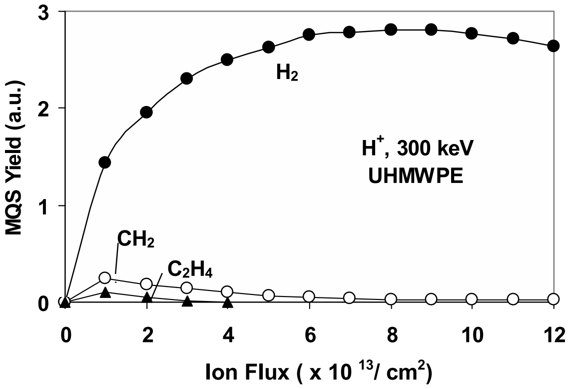


Fig. 2. MQS analysis: hydrogen production and CH_2 emission monitored during an UHMWPE sample bombardment with H^+ ions at 300 KeV energy versus the ion flux.

Mass spectrometry (MQA) measurements were performed on-line, during the ion implantation process. It was evidenced a high hydrogen and CH_2 production from the irradiated polymer. This result is not new and it is due to the UHMWPE C–H bond breaking and scission effects of the irradiated polymeric chains, as reported in literature [12].

Fig. 2 summarizes the results obtained by monitoring the mass 2 (upper curve) and mass 14 (bottom curve) emission as a function of the proton flux. The polymer dehydrogenation increases with the ion flux and saturates at a dose of about 8×10^{13} cm^{-2}. At higher doses the hydrogen emission decreases because the polymer becomes poor of hydrogen. Many C_xH_y groups are emitted simultaneously to the hydrogen but their yield is one order magnitude lower with respect to the hydrogen emission. Fig. 2 reports the monomer emission showing a decreasing yield with the ion flux.

The MQS signal due to other ion irradiation shows a higher yield in comparison to the proton irradiation and the hydrogen saturation region can be reached at lower doses with respect to the proton irradiation. Table 2 shows a lot of experimental data of H_2-MQS yield as a function of the ion stopping power for different ion doses. These results indicate that the polymer dehydrogenation is approximately proportional to the ion stopping power, according to literature [12].

The dehydrogenation process causes an increasing carbon concentration in the implanted surface that looks progressively dark. This is shown in the photo of Fig. 3, where white surfaces of UHMWPE became yellow after a low dose irradiation, then brown and finally black (similar to carbon) if the adsorbed irradiation dose is very high ($\sim 10^{15}$–10^{17} ions/cm^2).

The transmission ATR analysis of the pure and proton implanted samples confirms the result observed with MQS spectroscopy. It evidences, in fact, a C–H band breaking since the C–H stretching (Fig. 4a and b) and bending peaks (Fig. 4c) of the pure UHMWPE sample disappears after the ionic implantation at high dose (10^{17} H^+ ion/cm^2). Furthermore the –C=C– chemical bond with de-localized

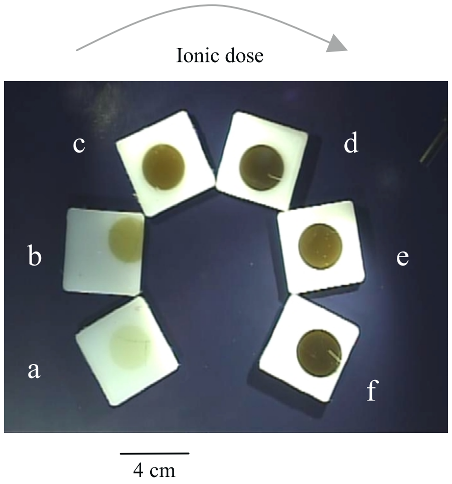


Fig. 3. Photos of the UHMWPE irradiated samples with: 1×10^{14} Xe^{+}/cm^{2} (a), 2×10^{14} Xe^{+}/cm^{2} (b), 4×10^{14} Xe^{+}/cm^{2} (c), 8×10^{14} Xe^{+}/cm^{2} (d), 1×10^{15} Xe^{+}/cm^{2} (e), 3×10^{15} Xe^{+}/cm^{2} (f).

charge is formed in the high dose implanted sample. The presence of this last peak suggests that after a high dose implantation, the polymer surface becomes poor of hydrogen and rich of cross-linked carbon atoms. In the same picture, the graphite ATR analysis was also reported for comparison. The graphite signal is a large peak in the range between 1400 and 1800 cm^{-1} due to the C–C stretching (see Table 3). The graphite C–C peak is quite coincident with that of the high dose implanted UHMWPE confirming that a graphite-like layer is present on the polyethylene sample.

Fig. 5 shows the intensity of a C–H stretching peak (at 2847 cm^{-1}) decreasing with the implantation dose of Xe^{+} and Ar^{+} ions. Furthermore this effect is more evidenced with increasing the ion stopping power and the ion dose.

Morphological SEM analyses have been performed on UHMWPE pristine and ion irradiated surfaces. Fig. 6a presents a homogeneous surface of pure UHMWPE, while

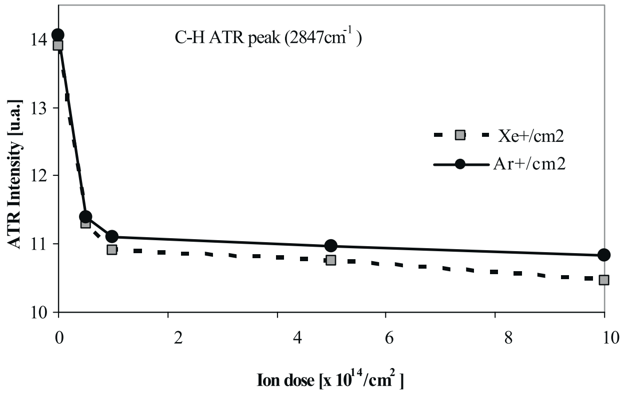


Fig. 5. Intensity of the ATR analysis C–H stretching peak at 2847 cm^{-1} versus the ion dose of Ar^{+} and Xe^{+} ions.

Fig. 6b shows the lamellar structure of the graphite-like material, produced by the high dose irradiation process ($10^{16}/cm^{2}$ Ar^{+} dose). This lamellar structure is similar to that of pure graphite showed in Fig. 6c and referred to a particular of its structure at 5000 ×.

The results of the Raman spectroscopy give another confirmation of the graphite-like structure produced by high dose ion irradiation (10^{17} H^{+}/cm^{2}). Fig. 7 shows the formation of the two peaks at about 1360 and 1590 cm^{-1} so called 'D-line and G-line' Raman peaks. They are typical, respectively, of disordered and ordered graphitic structure (middle spectrum), they are absent in the pure UHMWPE (bottom spectrum) and they are present in the proton irradiated UHMWPE (top spectrum).

The other narrow peaks present in the spectrum of the pristine UHMWPE are due to the semi-crystalline structure of the original polymer. The intensity of these peaks is reduced after the implantation process indicating a strong modification of the original structure.

The morphological measurements performed with the profiler evince a progressive surface roughness reduction with increasing the Xe^{+} ions dose, (until) from 35 nm (pristine) to about 10 nm (at 3×10^{15} Xe^{+}/cm^{2}). This value

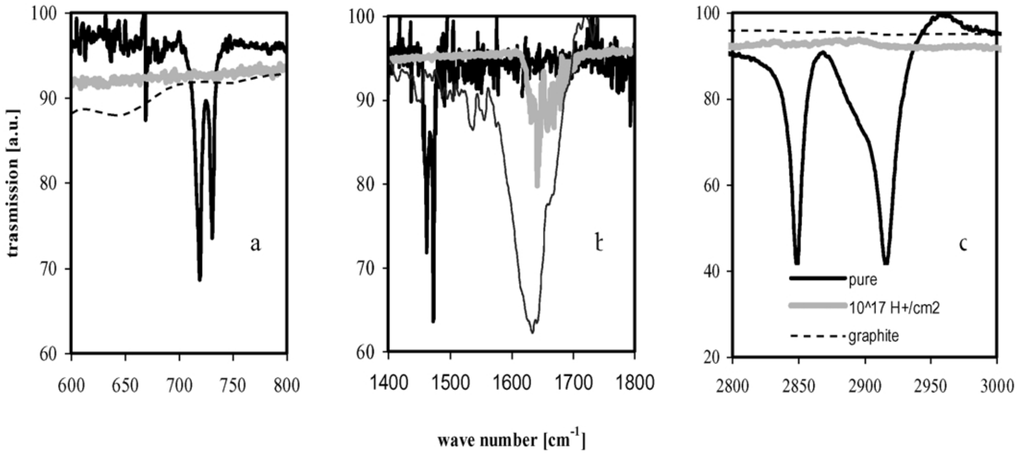


Fig. 4. ATR analysis of pure UHMWPE, high dose (1×10^{17} H^{+}/cm^{2}) irradiated UHMWPE and graphite samples at different wave numbers range: 600–800 cm^{-1} (a), 1400–1800 cm^{-1} (b) 2700–3000 cm^{-1} (c).

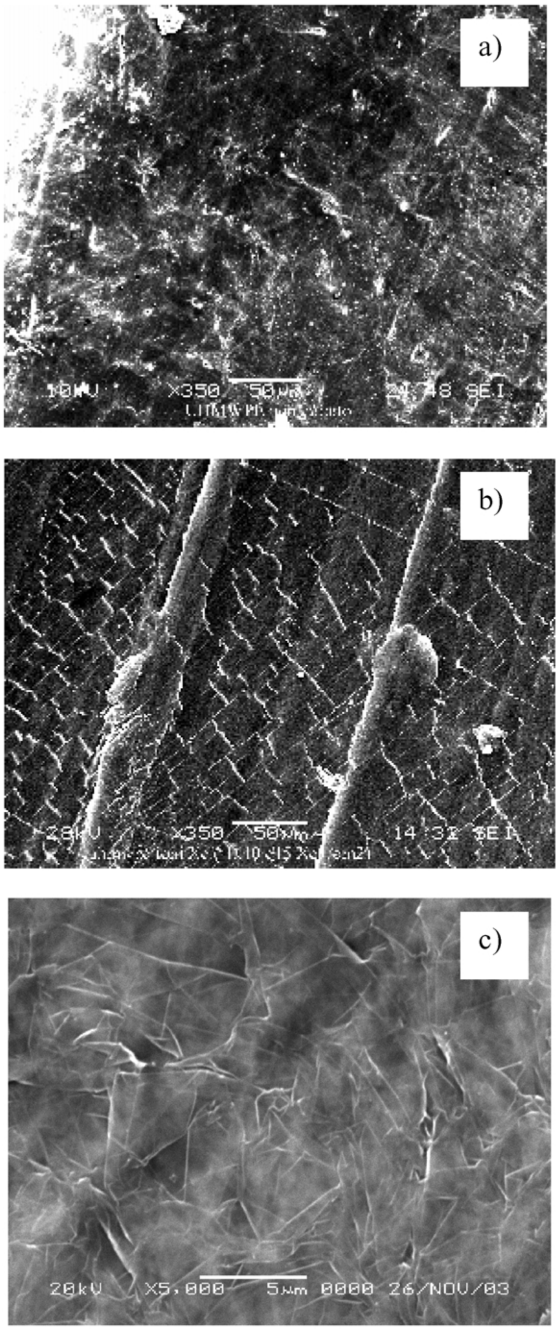


Fig. 6. SEM microscopy micrographs of pure (a) and 5×10^{15} Ar^+/cm^2 (b) UHMWPE sample at 350 × and of a SEM particular of pure graphite sample at 5000 × (c).

variation of about 86% suggests a strong smoothing effect of the ionic bombardment on the UHMWPE surface. Fig. 8 shows the average roughness of the polymer before and after the high dose implantation.

3.2. Mechanical characterization

Fig. 9a reports the weight loss values versus the sliding time of UHMWPE pure and irradiated with Xe^+ ions at a dose of $3 \times 10^{15}/cm^2$. The sliding time is in the range between 0 and 4320 min. The weight loss increases with the sliding time. The experiments are in agreement with the following empirical law:

$$Y = 0.0021 \ln(t) - 0.0017 \tag{4}$$

where Y is the weight loss given in mg and t is the wear time, in minutes.

The irradiation process reduces significantly the UHMWPE wear with respect to the pure sample and this effect increases with the implantation dose. Particularly, a wear reduction of about 76% is obtained in samples implanted at the higher dose (3×10^{15} Xe^+/cm^2).

In the same figure the weight loss values of graphite are reported for comparison. Very similar results are obtained for the standard carbon sample and the high dose irradiated UHMWPE sample. This result suggests that the graphite-like structure, produced only at the UHMWPE surface, has a similar wear behavior as typical for graphite.

In order to evaluate the wear resistance of UHMWPE surface at the body temperature, the polyethylene wear was studied also at 37 °C. Fig. 9b presents the results of wear tests performed in the temperature range 10–70°C. All polyethylene samples, implanted at different doses, show a weight loss increase with increasing the temperature. At body temperature, the wear is about 18% higher with respect to the value measured at the room temperature (22 °C).

Another mechanical characterization of the polymer was obtained by measuring its micro-hardness at the surface in the pristine and ion implanted polymers. The relative Shore values are plotted in Fig. 10 as a function of the irradiation dose for high stopping power ions (Xe^+). An increase of the surface micro-hardness with respect to the pure UHMWPE has been measured with the profiler. Particularly, in the sample implanted at 3×10^{15} Xe^+/cm^2, the micro-hardness, both statically and dynamically, is about 30% higher with respect to that of the pristine sample, having a shore hardness of 70 [16]. High implanted dose on UHMWPE don't reach the maximum value of 100 Shore, typical of graphite due to the thin surface layer on treated polymer under which pure UHMWPE is present.

4. Discussion and conclusions

Obtained results indicate that an UHMWPE polymer suffers of strong modifications when submitted to high dose ion implantation. Hydrogen and C_xH_y species are formed during the irradiation. The strong de-hydrogenation produces layers rich in carbon content, as demonstrated by different analytical analyses.

H* free radicals are formed and they diffuse in the polymer and then recombine until H_2 molecules are formed desorbing from the polymer surface. CH_2 and other CH groups are generated by H*, C* and C–H* radicals and scission processes of the polyethylene chains and they desorbs through the polymer. The hydrogen desorption is

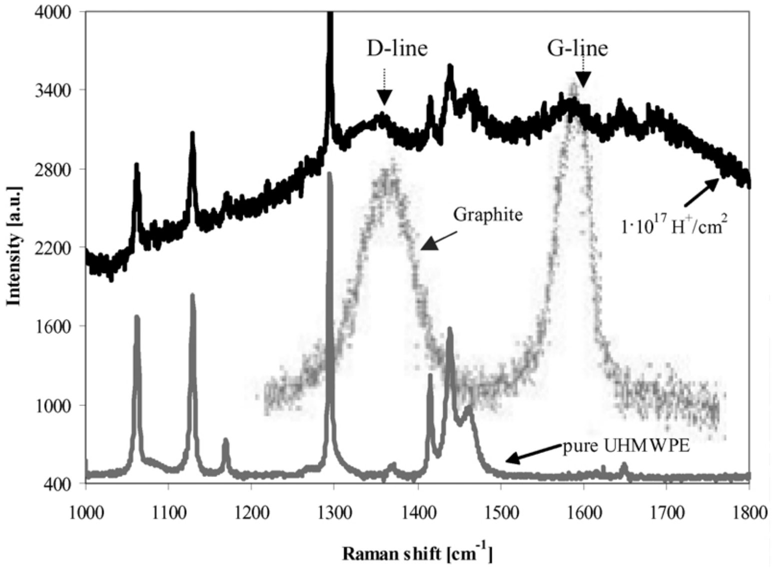


Fig. 7. Comparison of Raman spectra of a pure UHMWPE sample, an high dose (1×10^{17} H$^+$/cm^2) irradiated UHMWPE sample and a graphite sample.

more than one order of magnitude higher with respect to the CH groups. Desorption process decreases with the ion dose.

The residual polymer has a carbon-dehydrogenated structure that, at ion doses higher than 10^{15}/cm^2, resemble more and more to a graphite-like structure.

At high doses, in fact, the polymer has a black color and a high density. The mechanical wear resistance becomes high and comparable to that of amorphous carbon.

High doses treatments of polymeric surface smoothes the implanted area reducing the surface roughness and the friction.

The causes of UHMWPE improvement due to high dose ion implantation are different. As a first the energy release of the ions to the matter produces collisions between the projectile-ion and the target electrons and nucleus. The transferred kinetic energy occurs mainly along the latent tracks on the ions impinging on the polymer [17]. Into the latent track scissions and cross-linking effects take place; for example C–H bonds are broken and free hydrogen may outgas from the polymer, while the produced free radicals may induce new C–C bonds. At low ion dose, below about 10^{13} ions/cm^2, single tracks of modified polymer occur. At high dose on overlapping of tracks take place, inducing a global change of implanted surface. Of course the thickness of modified material will depend on the ion track length, i.e. on the range of the incident ion which is correlated to the ion stopping power. At high stopping power the ion track is large in diameter and short in length (such as for Xe ions).

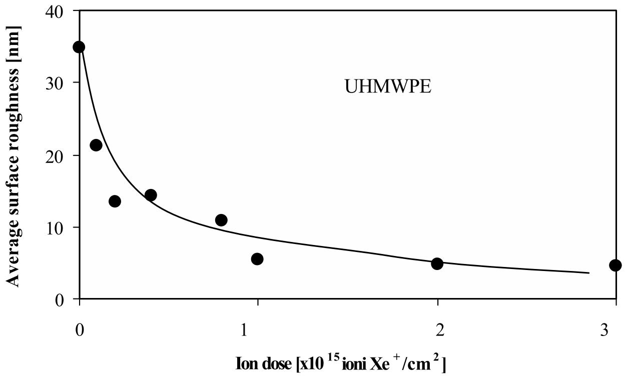


Fig. 8. UHMWPE surface roughness as a function of the Xe$^+$ ions irradiation dose.

In regime of track overlapping the network produced by C–C chemical bonds charge the density, the hardness, the electrical conductivity and other properties of the original polymer.

For ions having low stopping powers, such as H$^+$ and He$^+$, the track overlapping regime is obtained at higher doses with respect ions having high stoppings (Ar$^+$, Xe$^+$).

The UHMWPE is an insulating polymer and effects of charge-up were observed during the first phases of ion implantation. In order to avoid these effects, the ion currents were maintained low (~ 1 μA/cm^2) especially at low ion doses. At high doses ($\sim 10^{15}$/cm^2) the electrical conductivity of polyethylene is strongly modified and no any effect of charge-up can be observed. Literature reports that the electrical resistivity of such polymers may be reduced by about 4–5 order of magnitude due to the high dose ion implantation [12].

Graphite is a material that not only shows mechanical properties better than UHMWPE (hardness, mechanical strength, wear, Young modulus, friction coefficient,…) but also properties like high bio-compatibility and emo-compatibility [4,18]. It is for this reason that a graphite-like layer can be well used in friction surfaces such as the mobile prostheses.

The adhesion of the graphite-like structure on the polyethylene substrate is highest possible since chemical bonds are employed between the two layers. This aspect should be very important in biomedical applications like UHMWPE graphitization of cardiovascular prosthesis. In

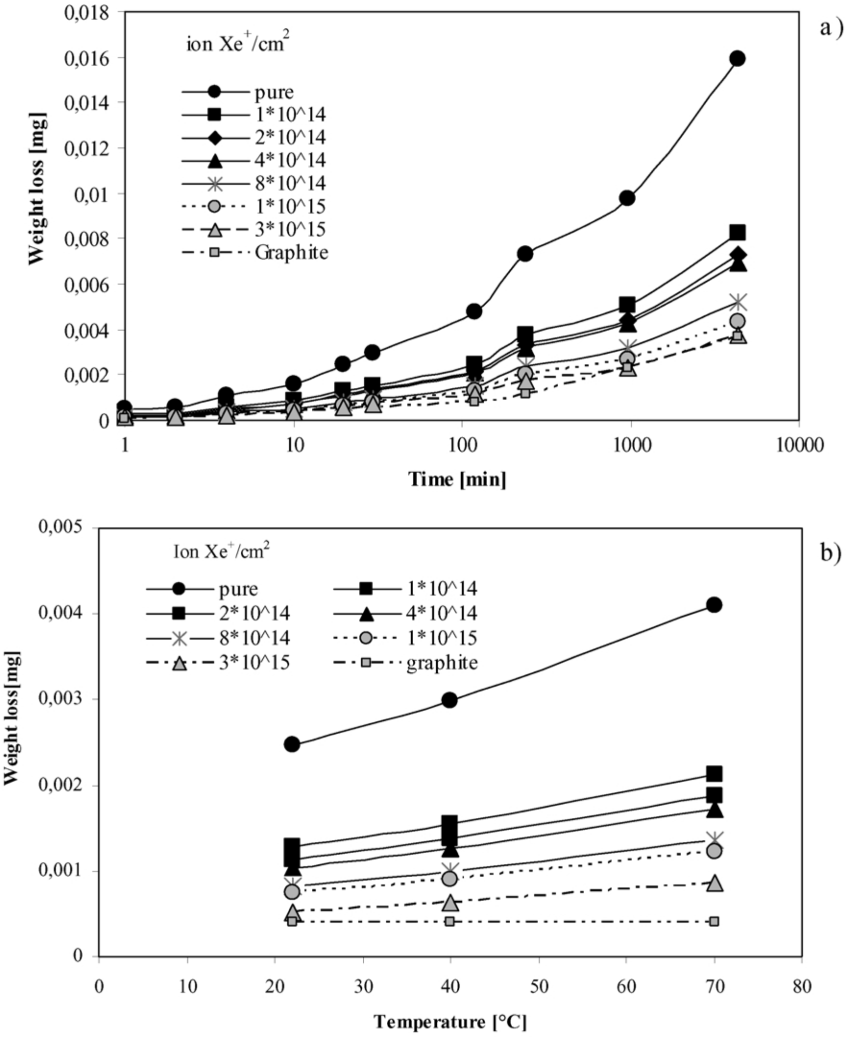


Fig. 9. Wear behavior of pure and irradiated with Xe^+ ions UHMWPE during the sliding time (a) and at different temperatures (b) The graphite data are reported for comparison.

this case, in facts, a graphite layer is necessary to increase the material emo-compatibility but a possible detachment could cause serious problems like thrombosis risk. In others applications, like friction bearings for mobile prosthesis, the high adhesion is an important aspect to guarantee the function of wear resistance improvement.

The ions used are able to control the surface modification deepness. For example, at 300 KeV of energy, it is possible to produce a graphite-like film of 3.8 μm deep with H^+ ions while a film of 0.2 μm deep is obtained with Xe^+ ions.

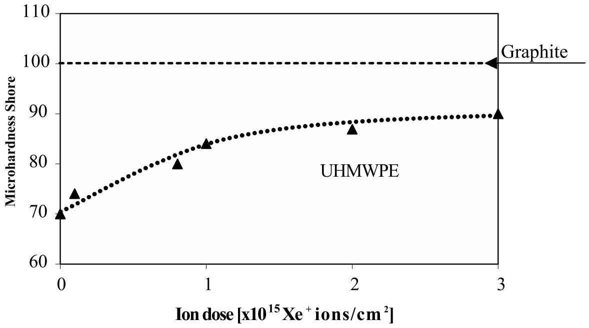


Fig. 10. Micro hardness of pure and implanted UHMWPE versus the implantation dose.

This work was a preliminary study of the ion-beam modified UHMWPE surfaces. Presented data are referred to very thin graphite-like films on the polyethylene sheet, which maximum thickness is 3.8 μm (for 300 keV proton beams). Unfortunately in this experiment we have not used high energetic ion accelerators giving higher ion ranges. Obtained results represent only data that confirms the wear reduction properties of implanted UHMWPE. Further investigations should be performed using more energetic ions (at MeV energy) having ranges higher than 100 μm, more useful and efficacious from the point of view of the application to the thick UHMWPE sheets of mobile prostheses. Furthermore, a multidirectional wear simulator and a protein containing lubricating will be necessary in order to produce the real bio-mechanical stresses acting on the UHMWPE devices used in the biomedical field.

In conclusion, the new properties given to the UHMWPE surface by ion implantation are very interesting to improve the functionality of mobile prostheses. The implantation reduces the wear and increases the surface hardness of the polymer; moreover its use, at the used ion doses, sterilizes the irradiated material. The surface wear resistance increases with increasing irradiation dose: a reduction of about 76% is noticeable after 72 h in a UHMWPE sample irradiated with 3×10^{15} Xe^{+}/cm^{2}.

The wear measurements presented in this paper differs from that presented in the recent literature [5,6]. The differences in the resulting weight loss can be due to the different operating conditions; in fact, in our experiment, the contact pressure, sliding distance and ion stopping powers are higher with respect the values employed in literature experiments.

References

[1] Wright TM, Goodman SB. Implant wear: the future of total joint replacement. Rosemont, IL, USA: American Academy of Orthopedic Surgeons; 1996. p. 1–22.

[2] Howie DW, Hanynes DR, Rogers SD, Mc Gee MA, Pearcey MJ. The response to particulate debris. Orthop Clin N Am 1993;24:571–81.

[3] Amstuz HC, Campbell P, Kossovsky N, Clarke IC. Mechanism and clinical significance of wear debris induced osteolysis. Clin Orthop 1992;276:7–18.

[4] Ravaglioli A, Krajewski A. In: Ravaglioli A, Krajewski A, editors. Bioceramics. London: Chapman and Hall; 1992.

[5] Chen J, Zhu F, Pan H, Cao J, Zhu D, Xu H, Cai Q, Shen J, He Z. Surface modification of ion implanted ultra high molecular weight polyethylene. Nucl Inst Methods Phys Res B 2000;169:26–30.

[6] Shi W, Li XY, Dong H. Improved wear resistance of ultra high molecular weight polyethylene by plasma immersion ion implantation. Wear 2001;250:544–52.

[7] Torrisi L, Gentile C, Valenza A, Visco AM. In: Torrisi L, editor. Grafitizzazione di polietilene (UHMWPE) tramite irraggiamento ionico per realizzare protesi emocompatibili. Proceedings of Sistemi biomeccanici ed interazione con i tessuti biologici, Catania: CNR; 2001. p. 48–56.

[8] Ziegler JF, Biersack JP. In: Ziegler JF, Biersack JP, editors. The stopping and range of ions in solids. New York: Pergamon; 1999.

[9] Torrisi L. Radiation damage in PVT (polyvinyltoluene) induced by energetic ions. Rad Eff Defect solids 1998;145:271–84.

[10] Giovannozzi R, 3rd ed. Costruzione di machine, vol. 1. Bologna: Patron Editor; 1997. Chapter 13.

[11] Mazzucco D, Spector M. Effects of contact area and stress on the volumetric wear of ultrahigh molecular weight polyethylene. Wear 2003;254:514–22.

[12] Venkatesan T, Calcagno L, Elman BS, Foti G. In: Mazzoldi P, Arnold GW, editors. Ion beam modification of insulators. Amsterdam: Elsevier; 1987. p. 301–79. Chapter 8.

[13] Fried JR. Polymer science and technology. Englewood Cliffs, NJ: Prentice-Hall; 1995.

[14] Silverstain RM, Clayton Bassler G, Morril TC. Spectrometric identification of organic compounds, 3rd ed. New York: Wiley; 1995.

[15] Evelyn AL, Ila D, Zimmerman RL, Bhat K, Poker DB, Hensley DK. Effects of MeV ions on PE and PVDC. Nucl Inst Methods Phys Res B 1998;141:164–8.

[16] Nielsen LE, Landel RF. Mechanical properties of polymers and composites. New York: Marcel Dekker; 1994.

[17] Sphor R. In: Bethge K, editor. Ion tracks and microeletronics. Vieweg; 1990.

[18] Brandrup J, Immergut EH, editors. Polymer handbook, 3rd ed. New York: Wiley; 1989.