J. Appl. Comput. Mech., 8(3) (2022) 1035-1042
DOI: 10.22055/jacm.2022.39555.3432

ISSN: 2383-4536
jacm.scu.ac.ir

Shahid Chamran University of Ahvaz

Journal of Applied and Computational Mechanics

Research Paper

Reducing the Wear of the UHMWPE Used in the Total Hip Replacement after Low-Pressure Plasma Treatment

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Received December 25 2021; Revised February 03 2022; Accepted for publication February 04 2022.
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Abstract. This paper discusses the problem of evaluating the microhardness gradient effect on surface wear of an ultra-high molecular weight polyethylene (UHMWPE) films treated with low-pressure plasma. Its solution was first obtained on the basis of the well-known Archard's wear law, modified taking into account the use of approximating dependences of negative depth gradients of surfaces microhardness, calculated on the basis of experimental data obtained by the nanoindentation method for samples with different plasma processing times (from 3 to 12 minutes). The wear evaluation was carried out in the ANSYS and MATLAB software in accordance with the requirements of ISO 14242-1 using the method of numerical simulation developed by authors. The simulation results show that such an integral parameter as cumulative volume wear is significantly lower for specimens treated with low-pressure plasma as compared to untreated ones. It has been found that both linear and cumulative volume wear decrease with an increase in the plasma processing time of the sample. The largest reduction (4 times compared to untreated) has been obtained for samples with a hardness gradient obtained by plasma surface treatment for 12 minutes. This time can be considered the maximum possible for processing UHMWPE with low-pressure plasma, since further increase in this time enhances the sample surface roughness and, consequently, the coefficient of friction. The use of low-pressure plasma treated UHMWPE films in THR will significantly reduce their wear and the likelihood of osteolysis, and thus increase the THR lifespan.

Keywords: Total hip replacement (THR); low-pressure plasma; UHMWPE; simulation; wear.

1. Introduction

Total Joint Replacement (TJR) is recognized as an effective treatment for severe joint injury and joint disease in humans. Currently, TJR is becoming increasingly important in medical practice due to a sharp increase in the number of diseases of natural joints due to unfavorable technogenic and environmental factors, which, in turn, contribute to the occurrence of joint diseases at a younger age [1]. The most typical of these is the human hip joint, the complete replacement of which with an artificial implant is called THR. It is known that THR sliding friction pairs can be divided into “hard” and “soft”, where “hard” contain a pair of metal-metal or ceramics-ceramics, and “soft” contain a pair of metal-ultra-high molecular weight polyethylene (UHMWPE) or ceramics-UHMWPE. Cobalt-chromium-molybdenum alloy (CoCrMo) is used as the metal element of the pair, and alumina or zirconia ceramics are used as the ceramic element. As a rule, the failure of a friction pair occurs due to the fact that in the process of its operation, wear of the mating surfaces occurs, as a result of which wear particles are released into the periprosthetic tissues. The immune system actively responses to these particles, dissolving the bone tissues connected with the implant, which leads to loosening of the implant, the occurrence of osteolysis and, thereby, to revision prosthetics.

One of the most commonly used prostheses in total hip arthroplasty (THA) is prosthesis with a “soft” pair of metal-UHMWPE or ceramics-UHMWPE. UHMWPE possesses good mechanical, physical and tribological properties, such as: biocompatibility, high hardness and durability, good chemical resistance, abrasion resistance, impact resistance, manufacturability, low friction coefficient and non-polarity of the polymer [2–6]. In addition, prosthesis with a “soft” pair is low-cost, and a pair of ceramics-UHMWPE has the lowest coefficient of friction [7]. It is also known that the human immune system responses mainly to the surface area of wear particles, and not to their number, and is activated when their total surface area reaches a certain threshold value [8]. In addition, when a metal-metal pair is worn, many particles are released, but they are very small, and in a pair with UHMWPE, few particles are released, but they are larger. And if we compare the total area of metal particles and polyethylene particles, it turns out that the area of metal particles is less than the area of polyethylene particles by only 30% [1], which once again confirms the popularity of prostheses with a “soft” pair, in particular, ceramics-UHMWPE.

Published online: February 15 2022

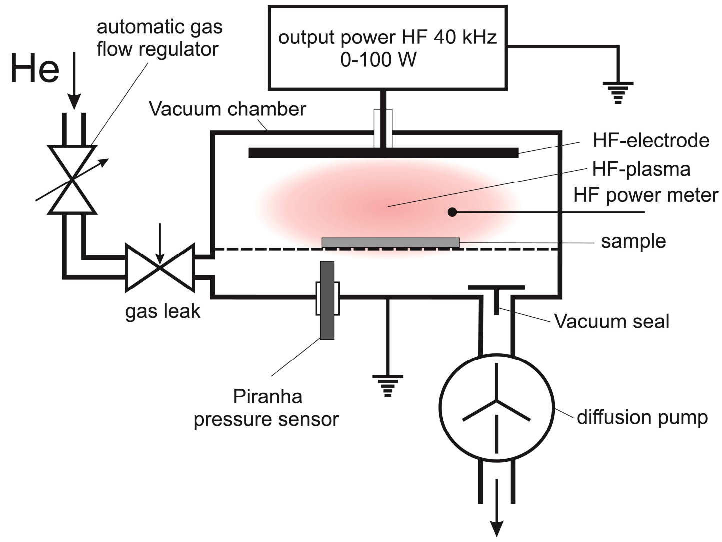

Fig. 1. Schematic experimental setup of low-pressure plasma treatment system.

Since UHMWPE is subject to wear, its particles activate osteolysis and aseptic loosening, which leads to ineffectiveness of THR and therefore the lifespan of UHMWPE joints is often limited to 15–20 years [9].

In recent decades, various attempts have been made to improve the wear resistance and performance of the material. In particular, the tribological properties of the polymer can be improved by crosslinking UHMWPE under gamma irradiation [10] or by introducing fillers into the polymer structure, which leads to a modification of the mechanical properties [11, 12]. Various researchers have tried to improve the tribological, mechanical, and thermal mass properties of the UHMWPE by reinforcement with various nanofillers, such as carbon nanotubes (CNT) [13, 14] or graphene oxide [15, 16] under the dry lubrication conditions. Researchers used CNT [17, 18] and graphene [19] as nanocomposite coatings based on UHMWPE. However, gamma irradiation leads to partial oxidation and destruction of the polymer, and the introduction of various fillers into the UHMWPE composition, along with an improvement in the surface tribological performances, is accompanied by a modification of its bulk mechanical properties, which does not always meet the requirements for the mechanical properties of an orthopedic material. Therefore, researchers are trying to improve the tribological properties of UHMWPE by creating a gradient structure of the polymer by strengthening its bearing surface without significantly changing the internal structure. This can be achieved either by crosslinking the surface layer of UHMWPE in a plasma of inert gases [20] or by applying a coating on the surface with increased tribological performances [19].

Commonly used coating methods include plasma surface modification using plasma spraying, implantation or deposition techniques [21] to improve surface properties such as wear resistance and hardness. Plasma Surface Modification (PSM) is an efficient and economical surface treatment method for many materials that is generating growing interest in biomedical engineering. The unique advantage of plasma modification is that surface properties and biocompatibility can be selectively improved, while the bulk performances of materials remain unchanged, and spatial surface shapes can also be processed [21]. There are, for example, reports on the treatment of UHMWPE surfaces with high-pressure plasma [22, 23]. But, as reported in [24], low-temperature plasma treatment will revolutionize the biomedical materials industry. And now, low-temperature plasma technology has found its application in biomedicine as a proven method for modifying the surface of biomaterials. When comparing low pressure plasma to atmospheric pressure, the low pressure plasma system (LPPS) is equipped with a pumping unit that consumes more power than the atmospheric pressure plasma system (APPS). However, LPPS requires less energy to generate and maintain a glow discharge compared to APPS. In addition, LPPS consumes less gas, which is important for applications that use expensive gases, as well as, the surface modification achieved with LPPS is more uniform and better controlled compared to APPS [24].

In this paper, we propose a technique for modification the surface of flat UHMWPE samples using low-pressure plasma in helium with different processing times. Fourier infrared spectroscopy was used to study the structure of the obtained surfaces. The microhardness of the treated and untreated samples surface was measured based of which a comparative correction of the wear factor in the Archard's wear law was performed. For a preliminary wear assessment of a THR acetabular liner made of UHMWPE, a comparative wear modeling with its treated contact surface and an untreated one was performed based on the method described in [25, 26]. There are also other methods for assessing wear in silico in a THR friction pair [27, 28], where a 3D contact-lubrication model and elasto-hydrodynamic lubrication conditions are used and are more computationally intensive. But these methods can be used if more accurate prosthetic wear calculation values are required. In this study, the main goal is to obtain comparative estimates of wear in the specified friction pair and thus a simpler simulation method was used. For the first time in this method, the account of the gradient change in hardness into the depth of the liner from its processed surface was carried out. It is assumed here that the liner bearing surface to be treated has a spherical shape. The simulation results will be further compared with the results of full-scale tests performed on a simulator [29], both under standard conditions of THR wear testing according to ISO 14242-1, and under conditions of patient's daily living [30], which will become the content of the next paper.

2. Materials and Methods

2.1 Material and Setup for Plasma Processing

UHMWPE samples 20 mm x 60 mm in size, 1 mm thick were made from commercially available orthopedic polymer Chirulen GUR 1020, (POLY HI SOLIDUR, Germany) by hot pressing. Then the samples were washed in ethyl alcohol. To treat the surface of the samples with low-temperature plasma, a standard device for plasma cleaning EV Plasma Cleaner 2.0L (Russia) was used, which is present in the experimental setup shown in Fig. 1. The samples were placed in a cylindrical vacuum chamber 100 mm in diameter and 270 mm in length, in which a discharge was ignited in a helium gas flow from a high-voltage generator with a frequency of 40 kHz at a power of 50 W, a pressure of 0.133 mbar (or 0.1 Torr), and a gas flow of 5 cm^3/min and processed for 3, 6, 9 and 12 minutes, respectively. The magnitude of root mean square roughness (RMS) was measured in this study by Atomic Force Microscopy (AFM Integra Spectra, Russia). Due to plasma ion etching the value of root mean square roughness (RMS) measured by AFM for UHMWPE increases initially slowly from 0.1 micron for the original sample to 0.13 and 0.15 micron for the samples treated in plasma 6 and 12 min. However, there is an abrupt increase RMS to 0.76 microns with increasing plasma treatment time to 20 minutes. The reason for such an abrupt increase in the etching rate and, as a consequence, an abrupt increase in microroughness, is the almost adiabatic heating of the sample under the action of plasma at low pressure in the absence of effective heat extraction. So, if treated for 6 and 12 minutes the temperature of the UHMWPE sample rises from room temperature only to 50 C and 70 C, respectively, then treatment for 20 minutes in plasma leads to a strong increase in temperature to 210 C, which causes to abrupt increase in the plasma surface etching rate, increase of microroughness of the sample surface and finally leads to abrupt increase of coefficient of friction. That is why 12 min appears to be the time limit under the given plasma processing conditions.

2.2 FTIR Spectroscopy

Changes in the chemical composition of the UHMWPE surface before and after treatment with helium plasma at low pressure are studied by Fourier-transform infrared spectroscopy (FTIR). To record the surface infrared spectra, a Perkin Elmer 1720X FTIR spectrometer with an Attenuated Total Reflectance (ATR) attachment on a 45° ZnSe crystal (USA) and an FT-801 FTIR spectrometer (Russia) with an ATR attachment with a ZnSe crystal were used.

2.3 Nanoindentation Study

The instrumental microhardness (MPa) of the studied samples of UHMWPE was measured with a desktop nanoindentation system NHT2 TTX (CSM Instruments SA, Switzerland), in which the load range is 0.025 to 100 mN with a resolution of 0.001 mN and a maximum indentation depth of 100 µm with a depth resolution of 0.001 nm. The measurement process was carried out by pressing a Berkovich diamond nanoindenter sharpened in the shape of a trihedral pyramid into the surface of the samples. In order to check the reproduction of the processing results, the resulting dependence of the hardness on the depth H=H(z) for each sample was plotted in a series of five separate measurements. The use of the Berkovich indenter is caused by the fact that a real pyramidal indenter is not ideally sharp since at its apex there is always a blunt zone close in shape to a sphere. For a more accurate measurement of the hardness of soft samples, it is necessary that the radius of curvature is much smaller than the size of the indentation. For the Berkovich pyramid, it is ~ 40 nm. For comparison, the Vickers indenter has a radius of the pyramid top curvature of at least 1 micron. Therefore, the use of a Berkovich indenter makes it possible to carry out measurements at much lower loads than when using a Vickers indenter, which in this case was one of the main conditions for carrying out reproducible measurements of sufficiently soft samples of UHMWPE.

2.4 The Wear Simulation of the THR UHMWPE Liner Spherical Surface

The wear simulation of a THR acetabular liner made of UHMWPE with both treated and untreated contact surfaces was carried out according to the method described in detail earlier in [25, 26]. The model contains a hard spherical femoral head made of CoCrMo alloy with a widely used standard diameter of 32 mm, mated to a soft acetabular cup made of UHMWPE. The radial clearance between the elements of the friction pair is 0.15 mm. The moduli of elasticity and Poisson's ratios are taken equal: for the cup is E_c = 800 MPa, ν_c = 0.46 [31]; for the head is E_h = 210 GPa, ν_h = 0.3. The model of the spherical joint of the right THR, shown in Fig. 2, is defined in a fixed anatomical coordinate system $x'y'z'$. When modeling wear, a simplified XYZ coordinate system is used, rigidly connected to the cup with the origin located in its center (Fig. 3). The origin of the movable coordinate system xyz, used to determine the Euler angles, is rigidly connected with the center of the head and coincides with the center of the cup. The head has three rotational degrees of freedom, commonly referred to as FE (flexion-extension), AA (abduction-adduction), and IER (internal-external rotation).

Wear simulation is based on its simple form, the classic Archard's law, which in general form for ideal uniformly loaded isotropic surfaces with nominal contact pressures in a linearly elastic domain can be represented as the equation:

$$V = k\frac{p}{H}S\,, \tag{1}$$

where V is the total amount of wear; k is known as the adhesive wear factor; p is an average contact pressure; H is the hardness of the softer material; S is a sliding distance.

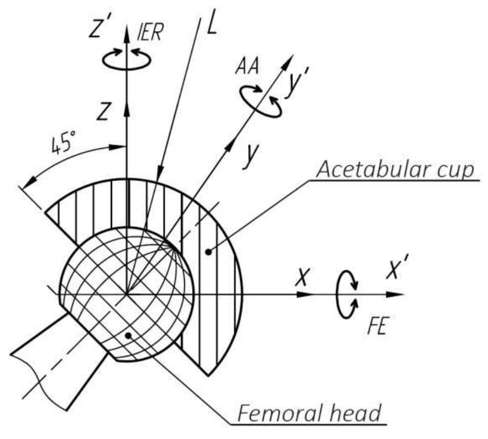

Fig. 2. Front view of the right hip joint with the directions of rotation shown (L is the vector of the resultant load) [25, 26].

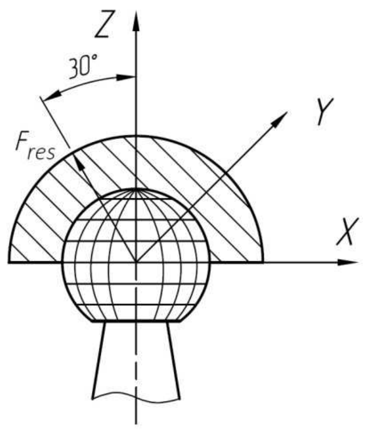

Fig. 3. The simplified spherical coordinate system for use in wear simulation (F_{res} is the resultant force vector) [25, 26].

It should be noted that although the Archard equation was developed for adhesive wear, it is widely used to simulate abrasive, fretting, and other types of wear [32]. It is also known that the Archard eq. (1) is often applied at the local level. To do this, both of its parts are formally divided by the area and, therefore, we obtain:

$$h = k\frac{\sigma}{H}S\ , \tag{2}$$

where h is the local depth of wear and σ is the local normal contact pressure.

But, as a rule, the surface hardness in many cases is very difficult to estimate and then eq. (2) is used in the form:

$$h = k_w \sigma S\ , \tag{3}$$

where $k_w = k / H$ and already this coefficient is taken in the form of the actual wear factor.

The wear factor k_w depends on the material, the nature of the surface and, as has been found, on the normal contact pressure. Various dependences of k_w on the contact pressure were investigated in [25] and it was shown that the most reliable form can be represented as:

$$k_w = 2\cdot 10^{-6}\sigma^{-0.84}\ . \tag{4}$$

Following [26] and substituting eq. (4) into eq. (3), we obtain the formula:

$$h = k_w\sigma S = \frac{2\cdot 10^{-6}}{\sigma^{-0.84}}\sigma S = 2\cdot 10^{-6}\sigma^{0.16}S\ . \tag{5}$$

One of the serious limitations of representing Archard's law in the form of eq. (5) is the lack of consideration the hardness of surface subjected to wear. Therefore, for the first time, it is proposed to take into account the surface hardness, given that in this study the problem is to perform mainly a comparative calculation in order to see a qualitative impact of the specified surface treatment on wear. For this purpose, denoting the hardness of the untreated UHMWPE sample as H_1, and the treated one as H_2, the depth of wear h for the untreated sample will be calculated according to eq. (5), and for the treated one according to the formula:

$$h = \frac{2\cdot 10^{-6}}{H_2}H_1\sigma^{0.16}S\ . \tag{6}$$

It is also known that plasma treatment creates a gradient structure of the material in terms of hardness inward from its processed surface [33]. Therefore, if using nanoindentation to measure the hardness along the depth of the untreated and processed samples, and represent them in the form of the dependence $H = H(z)$, then using eq. (6) it is possible to obtain the local depth of wear h of the treated sample, and using eq. (5) as the untreated one.

Further, eq. (2) can be described in discrete form in a spherical coordinate system at the point of the contacting surface as a local increment in the depth of wear $\Delta h(\theta,\varphi)$, taking into account eq. (5) and eq. (6) by the following equation [34]:

$$\Delta h(\theta,\varphi) = \sum_{i=1}^{n} k_{wprop}\sigma^{0.16}(\theta,\varphi,t_i)\Delta S(\theta,\varphi,t_i)\ , \tag{7}$$

where $\sigma(\theta,\varphi,t_i)$ is the normal contact pressure between two interacting surfaces at the same point at the time of the gait cycle; t_i is the increment in the length of the sliding arc $\Delta S(\theta,\varphi,t_i)$ between adjacent design points under the same conditions; k_{wprop} is the proportionality factor:

$$\begin{aligned} k_{wprop} &= 2\cdot 10^{-6} \text{ for the untreated sample,} \\ k_{wprop} &= 2\cdot 10^{-6}\, H_1/H_2 \text{ for the treated sample.} \end{aligned} \tag{8}$$

The finite element analysis of the model for calculating the depth of wear, built taking into account eq. (7), was carried out in the ANSYS and MATLAB software. In this case, to determine the increment in the length of the sliding arc $\Delta S(\theta,\varphi,t_i)$, we used the kinematic diagrams of the angular displacements of the joint femoral component, and when determining the normal contact pressure $\sigma(\theta,\varphi,t_i)$ by solving the contact problem, we took into account the change in the magnitude of the applied force vector at the length of the step. The calculation algorithm was presented in detail in [26, 29], in which the parameters of wear during normal walking were investigated in two versions: according to the requirements of ISO 14242-1 and for the angular positions of the hip measured by Jonhston and Smidt, taking into account the diagrams of the applied force measured by Paul [35]. In this study, wear simulation was carried out only in option according to requirements of ISO 14242-1 on kinematic and applied force conditions, although with the same success it was possible to carry out the simulation process according to another option, since the modeling method easily allows this.

3. Results and Discussion

3.1 FTIR Spectroscopy of UHMWPE

The treatment of UHMWPE in helium plasma at low pressure leads to the appearance in the infrared spectrum of UHMWPE surface layer a new absorption band corresponding to the wavelength λ = 965 cm^{-1} (Fig. 4), which, according to the literature, can be attributed to double bonds. The concentration of double bonds, proportional to the relative intensity of this absorption line to the absorption line at λ = 1470 cm^{-1}, corresponding to the deformation vibrations of the C-H bond, goes to the limit value in 12 minutes of plasma treatment at a power of 50 W and a helium pressure 13.3 Pa and gas flow of 5 cm^3/min. The formation of double bonds occurs, obviously, under the action of chemically active components of the plasma, such as vacuum ultraviolet radiation, electrons and ions coming to the surface of the polymer sample. In this case, the primary process is the dissociation of C-H bonds and detachment of atomic or molecular hydrogen from the polymer molecule with the formation of alkyl radicals. Subsequently, recombination of these radicals with the formation of double bonds, if the radicals belong to neighboring atoms of a polymer molecule, or intermolecular crosslinking, if the radicals are located on neighboring molecules, take place. Thus, the formation of double bonds is always accompanied by the formation of intermolecular crosslinks. Unfortunately, in accordance with the rules of symmetry, cross-links do not appear in the infrared spectra. However, there are publications where the formation of double bonds is used as an internal probe to determine the degree of crosslinking in UHMWPE [36]. In our case, it is important that the formation of crosslinks in the surface layer leads to an increase in the surface strength parameters of UHMWPE and, ultimately, to an increase in its wear surface resistance.

3.2 Nanoindentation Measurements

Due to the fact that the studied samples had a sufficiently developed relief, in order to obtain high-quality imprints of the pyramid tip, it was necessary to carry out measurements at depths several times greater than the dimensions of the surface irregularities (tens and hundreds of nanometers). For this reason, the reproducibility of the results in our case was achieved starting from depths of 600 nm (Fig. 5). In order not to clutter up the image, in Fig. 5 shown curves, each of which is averaged over five dependencies of $H=H(z)$, the average deviations for which do not exceed ± 5%. Moreover, in almost all cases, $H=H(z)$ are described by complex polynomials of the seventh degree, for the approximation of which arrays of nine points were used (Table 1). The seventh order of the polynomial is the minimum order that provides satisfactory agreement with the experiment. This fact excludes the diffusion mechanism of modification of physical properties (microhardness) in the near-surface region and, in all likelihood, indicates the presence of a certain multistage process. To estimate the values of H on the surface itself, the polynomials were approximated to the point of z=0. In Fig. 5, these initial portions of the curves are shown by dashed lines.

As follows from Fig. 5, the main changes in microhardness occur in the near-surface region at depths of up to 2 μm, after which the dependences $H=H(z)$ reach a constant value corresponding to the volumetric average values of microhardness $H≈65$ MPa. An increase in the processing time from $t = 3$ min to $t = 12$ min in most cases leads to a progressive increase in the values of H in the near-surface region, which is especially well manifested in the initial sections of $H=H(z)$. So, if during the treatment time of 6 min the average rate of change in the magnitudes of H is ≈2.5 MPa/min, then for the treatment time of 12 min it reaches ≈12.5 MPa/min. This indicates a strong nonlinearity of the processes occurring in the near-surface region during plasma processing.

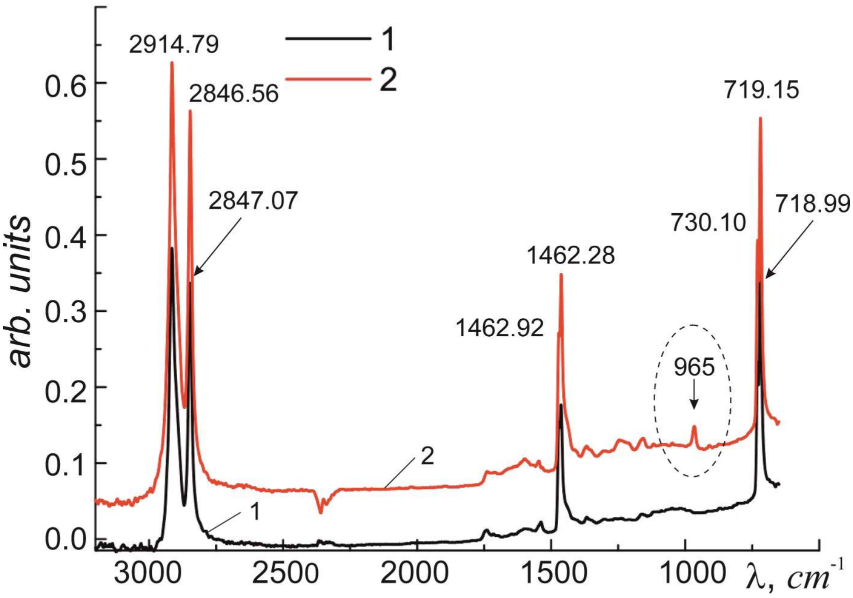

Fig. 4. FTIR spectra of UHMWPE before (black is 1) and after (red is 2) treatment in helium plasma at low pressure (discharge power of 50 W, helium pressure of 13.3 Pa and helium flow of 5 cm^3/min).

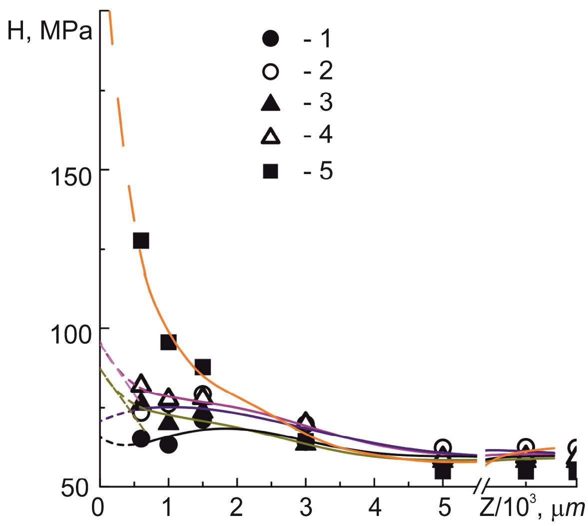

Fig. 5. Plots $H = H(z)$ depending on the duration of samples treatment: 1 is initial untreated, 2 is $t = 3$ min, 3 is $t = 6$ min, 4 is $t = 9$ min and 5 is $t = 12$ min.

Table 1. Approximating polynomials for the curves shown in Fig. 5.

Curve number	Polynomials (H in MPa, Z in nm)
1	H = 65.84832-0.01633 Z +3.17652E-5 Z^2 -2.02908E-8 Z^3 +5.98269E-12 Z^4 -9.07865E-16 Z^5 +6.90095E-20 Z^6 -2.08234E-24 Z^7
2	H = 70.7935+0.00946 Z -5.75013E-6 Z^2 +9.20145E-10 Z^3 -4.58763E-14 Z^4
3	H = 87.29699-0.03588 Z +3.54138E-5 Z^2 -1.86938E-8 Z^3 +5.11657E-12 Z^4 -7.45687E-16 Z^5 +5.51429E-20 Z^6 -1.62862E-24 Z^7
4	H = 95.59367-0.04184 Z +3.97469E-5 Z^2 -1.95533E-8 Z^3 +4.96639E-12 Z^4 -6.75725E-16 Z^5 +4.70593E-20 Z^6 -1.32073E-24 Z^7
5	H = 238.97592-0.31952 Z +2.73785E-4 Z^2 -1.24781E-7 Z^3 +3.14332E-11 Z^4 -4.38766E-15 Z^5 +3.1752E-19 Z^6 -9.28422E-24 Z^7

3.3 Coefficient of Friction

The coefficient of friction (CoF) for UHMWPE samples was also experimentally measured under dry lubrication conditions with reciprocating motions by the Labthink MXD-02 Coefficient of friction tester (China) with a pressing force of $F\approx1.96$ N. The results were averaged over three measurement points. The magnitudes of the CoF increased in the range from 0.155 for the untreated sample to 0.525 for the sample treated with plasma during 12 minutes. An increase in the average roughness dimensions with a raise in the processing time correlates well with enhance in the CoF. This is an indirect confirmation of the fact that an increase in the duration of processing contributes to a greater damage to the surface.

But in a real THR friction pair, there are boundary and even mixed lubrication conditions and, according to the study [37], when one step of walking, the average CoF increases from 0.04 (0.03 to 0.06) at contralateral toe off phase to 0.06 (0.04 to 0.08) at contralateral heel strike. During the flexion phase, the CoF raises further to 0.14 (0.09 to 0.23) at toe off phase.

3.4 The Wear Simulation in a THR Friction Pair with a UHMWPE Liner

The wear simulation was performed in accordance with the requirements of ISO 14242-1 during normal human walking, where up to 5 million cycles (human steps) the dependences of the change in the maximum linear wear and the cumulative volumetric wear were obtained. In this case, the term of maximum linear wear is used as the value of linear wear, which is the maximum among the magnitudes for all model nodes. The cumulative volumetric wear is calculated in the model as the extracted volume of the ball segment into which the head is deepened. When simulation, the magnitude of one deepening step was investigated and a step with 250,000 cycles of human steps was chosen, which, compared with smaller magnitudes of such a step, gives an error within 1%. In 5 million cycles of human steps, the number of such deepening steps equals of 20. According to [37] and taking into account the range of change in the value of the CoF for one cycle (one walking step), its value for the simulation was taken to be 0.1. Fig. 6a shows the change in the maximum linear wear of the liner contact surface, both with the initial untreated and treated with plasma for 3, 6, 9 and 12 minutes, and Fig. 6b shows the change in its cumulative volume wear for the same conditions.

Analysis of Figs 6a and 6b shows that taking into account the presented gradient change in the hardness of the UHMWPE film inward from its surface provides, for 5 million normal walking cycles, a decrease in the maximum linear wear of samples treated with plasma for 3, 6, 9 and 12 minutes, approximately by 1.16, 1.37, 1.65 and 6.4 times, respectively, compared to the original material. And for volume wear, these values are approximately 1.09, 1.38, 1.53, and 4 times, respectively. Hereby it can be seen that the best result in increasing the wear resistance is obtained by treating the samples with plasma for 12 minutes. The most reliable in this case is the parameter of cumulative volume wear, since, according to its calculation method, it is an integral parameter that ensures the occurrence of a lower errors probability in its calculation. If we now consider that, on average, a person makes 1 million steps in 1 year with normal walking [35], then, focusing on the volume wear of a specimen processed for 12 minutes, and under the same operating conditions of THR, its lifespan can be increased by approximately 15 years more, which is the most important performance of the patient's life quality.

The initial contact of the THR head with the liner surface begins with a point and as the head wears and, thus, deepens into the liner, the contact area increases, and the number of finite element model nodes involved in the contact, which must first pass through the gradient zone of the liner surface with higher hardness also increases. Due to the spherical shape of the contact surface, as it wears, a significant number of nodes stay in this gradient zone of microhardness for a long time, although its depth is small, which helps to reduce the wear of this surface. In this case, the wear pattern of the flat UHMWPE samples interaction surface due to it geometry will obviously differ from the wear of spherical one.

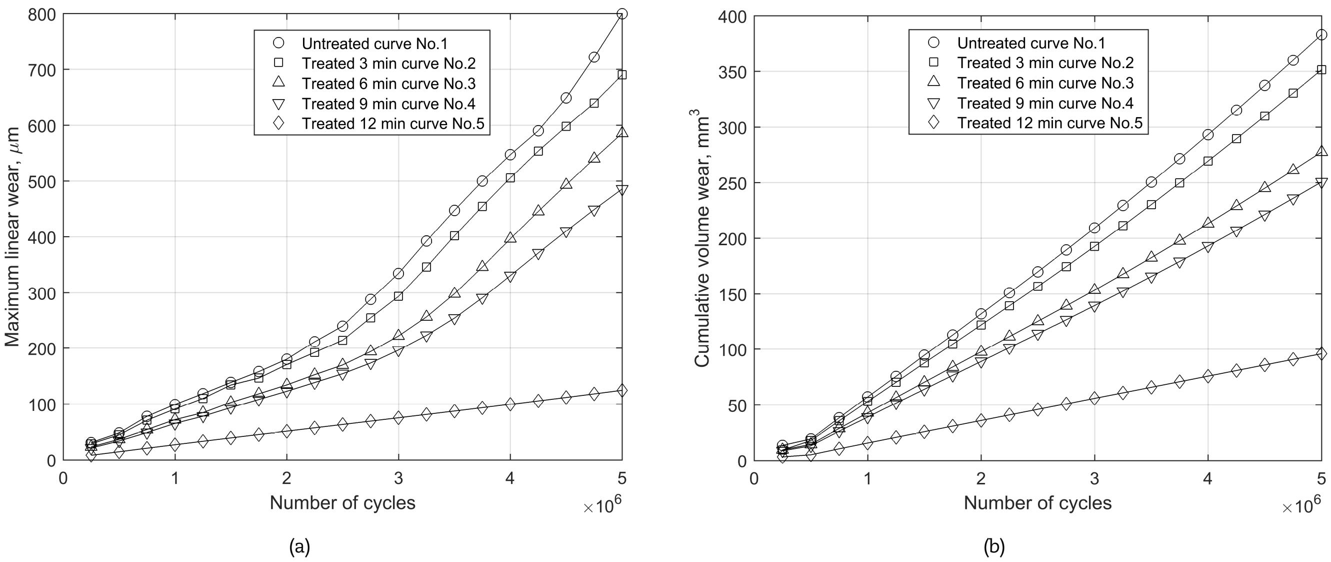

Fig. 6. Plots of changes in the maximum linear (a) and cumulative volume wear (b) of the THR liner contact spherical surface for the original untreated sample with number 1, and processed samples with duration time at numbers: 2 is 3 min, 3 is 6 min, 4 is 9 min, and 5 is 12 min.

4. Conclusion

The tribological properties of UHMWPE can be significantly improved by treating the surface with low-pressure plasma following by the increase of surface hardness, changing with a negative gradient deep into the material. Such processing of samples with a treating time in the range from 3 to 12 minutes and further measurement of their microhardness deep into the material showed the greatest increase in hardness at 12 minutes of processing. The approximation of the obtained results of measuring the microhardness in the form of analytical dependences made it possible for the first time to take them into account the hardness in the Archard's wear equation. Thus, taking into account this correction of the Archard equation, it was possible to perform numerical wear simulation in a spherical metal-UHMWPE friction pair of a THR in accordance with the requirements of ISO 14242-1 up to 5 million cycles (walking steps) according to the technique previously developed by the authors. As a result of simulation, considering cumulative volume wear as the most reliable integral parameter, its reduction at the indicated number of cycles turned out to be approximately in the range from 1.09 to 4 times as the processing time increased. The largest reduction (up to 4 times) is achieved with a processing time of 12 minutes. Due to the specified processing method, the THR lifespan is increased, which is the most important performance of the patient's life quality.

Simulations in this paper have been carried out under assumption of the Archard’s law validity in its simplest form. However, it is known that it is only a very rough approximation. Under certain conditions, the wear in a given tribological pair can increase dramatically or vanish almost completely [38]. It would be interesting to find out the conditions for transitions between “normal” wear, severe wear and almost wear-less conditions. Further, in the present approach we have not explicitly considered the transport of the wear particles in the frictional zone, which, however, may significantly influence the wear process [39]. Finally, it would be interesting to consider a possibility of similar simulations using the Boundary Element Method which has shown its specific efficiency for simulation of contact problems [40].

Author Contributions

Vladimir Pakhaliuk made analytical model of simulation, carried out the numerical simulation, and drafted the manuscript. Victor N. Vasilets created the main idea of UHMWPE treating and its experimental embodiment. Aleksandr Poliakov carried out the treating experiment and processed experimental data. Nikolay Torkhov carried out nanoindentation measurements and processed experimental data. All authors contributed equally to the editing and reviewing the manuscript.

Acknowledgments

The authors acknowledge a Doctor G.D. Olinichenko, Ph.D. in medicine, for his helpful comments in preparing this paper.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Funding

The authors received no financial support for the research, authorship, and publication of this article.

Data Availability Statements

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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How to cite this article: Pakhaliuk V.I., Vasilets V.N., Poliakov A.M., Torkhov N.A. Reducing the Wear of the UHMWPE Used in the Total Hip Replacement after Low-Pressure Plasma Treatment, *J. Appl. Comput. Mech.*, 8(3), 2022, 1035–1042. https://doi.org/10.22055/jacm.2022.39555.3432