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Experimental Research of the Durability and Wearing of UHMWPE with Different Coatings

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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Short Research Article

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ABSTRACT

In the paper UHMWPE coating with different materials is analysed. Such coatings are made using magnetron sputtering method. The friction tests of these coatings are accomplished. SPM surface morphology images of coatings are analysed before and after the friction test. It was determined that $Co+TiO_2$ coating altered the least after the friction tests. For this reason, its durability and wear resistance is the highest in comparison with all the analysed coatings.

Keywords: Coating; scanning probe microscope; durability.

1. INTRODUCTION

Development of replacement arthroplasty touched a number of problems. These problems include the design of the implanted components, a way of their fixation, properties, rubbing surfaces and their wear resistance [1,2,3]. In scientific publications of the last decade the consequences of the wear of articular surfaces, such as osteolysis and survival of mechanical fixing components, are frequently discussed [1,4]. Osteolysis is understood as a bone

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resorption or the massive formation of cystic granuloma around an implant [1,4,5]. The bone resorption around the implanted hip joint components is one of topicalities of today's surgical replacement arthroplasty that predetermines the service life of the mechanical fixtures of the implanted components [4].

For manufacturing the components of an artificial hip joint various materials are used; they include metals and their alloys (titanium and its oxides, stainless steel, cobalt-chromium-molybdenum alloy) [2,3,6], ceramics (aluminum oxide, zirconia) [7,8,9] and polymeric materials (PMMA, UHMWPE) [6,10,11].

Polymeric materials used in the production of the implants have become abundant; however, for over 40 years, Ultra-High Molecular Weight Polyethylene (UHMWPE) is used in the production of hip joint endoprostheses [6]. The said material is used for producing the insert of the hip joint socket [6,7]. It is distinguished for its low friction coefficient, good biocompatibility and lubricant properties; however, its fracture resistance is lower, leading it to a rapid wear. In addition, particles of worn polyethylene get into the body and cause the undesirable reaction of the tissues, known as osteolysis [4,5]. In such case, patients become the subjects for the revision surgery of the hip joint replacement arthroplasty.

At present, the modification of metal or plastic surfaces of the implants is very often analyzed [12,13]. The modification of a polymer surface, either by chemical or physical methods, is very important in order to achieve its new uses and different properties. This is especially true when referred to inert polymers, as is the case of polyethylene, whose surface needs etching treatments to improve their biocompatibility and their adhesion [5,10,11].

The previous researches have shown that when the elastic module of the material of hip endoprosthesis socket is low and the stiffness of femoral stem is high, the pressure in contact surfaces is reduced considerably, lubrication conditions are improved and the durability of hip endoprosthesis is increased [14]. The researches have shown that when coating the polyethylene surface of the socket with durable TiO_2 and Co-Cr-Mo coatings, on one side the surface contact is hardened but on the other side it is coated on a resilient base and this allows it to increase the surface contact [15]. Such solution helps reduce stress and considerably improve the wear-and-tear resistance. The above combination can be applied in the fields where it is crucial to extend service life of frictional parts and units that are featured for their restricted lubrication properties undertaking damping of vibrations and impacts.

UHMWPE is coated with different coatings to improve its mechanical properties & durability and to reduce its wear herewith the number of fragments that cause host reaction to the artificial hip joint [15]. However, only primary tests on durability of the said coatings were carried out in the above-mentioned works as of 2500 friction cycles only. This number is too low because the joints on their movement are subjected to considerably higher number of cycles. In addition, various coatings, for instance, zirconium and zirconia can be used. Zirconium is distinguished for its good biocompatibility properties and its elastic module is close to the elastic module of human bones. Zirconia is highly biocompatible, as are other ceramics, and can be made in the form of large implants such as the femoral head and acetabular cup in total hip joint replacement [16]. In the present research, the coatings of UHMWPE with zirconium, zirconia, titanium oxide and cobalt-chromium-molybdenum alloy were applied to carry out friction tests on a stand, to examine the microstructure of the coatings by a scanning probe microscope (SPM) before and after the friction tests to identify what coating withstood 10 000 working cycles in the best way.

2. MATERIALS AND METHODS

For the formation of the coatings, 3-source magnetron sputtering SCM was used. Coatings were made with such parameters of the system: Ar+ ion flow 20 cm^3/min; operating pressure 0.6 Pa; deposition time t = 60 min; current strength I = 0.8 A; voltage U =270 V. Distance between magnetron and substrate 27,0±2 mm. Three specimens were prepared for each coating group (Co-Cr-Mo, Co+TiO_2, Zr and ZrO_2). *Chirulen* (ISO5834-2, *POLY Hi Solidur Medi TECH Company*), special designation (for medicinal purposes) high molecular weight polyethylene has been used for investigation purposes.

The surface of samples has been measured by scanning probe microscope (SPM) (Dimension 3100, Digital Instruments, USA). The instrument operates under atmospheric pressure at room temperature (20-22ºC) and works in air. Samples' diameter is 10 mm, height is 7 mm.

The SPM is equipped with an in-line optical zoom microscope with color CCD camera, with a maximum magnification of 800x for precise placement of the SPM probe onto the sample. Measurements include surface roughness and particle size, with a noise floor in height measurement of 0.02 nm.

Coatings have been tested for their abrasion resistance and durability. For this purpose a special rubbing device generating friction effect has been designed and manufactured (Fig. 1).

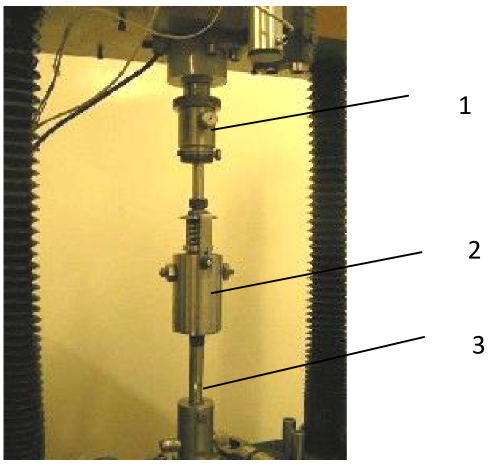


Fig. 1. Device and its parts: 1– FP-10 tensioning equipment; 2 – special device; 3 – rod

The device for the stand is intended for operation in the FP-10 tensioning equipment (Heckert, Germany). The stand is used for simulation of real movements taking place in the human hip joints. One cycle is back-and-forth motion of the stand's rod 3. Within such cycle a sample inserted in the fixture 2 is loaded from 0 to the maximum force (400 N) and it is rotated at a certain angle (-2º - +2º). Within one cycle the sample performs a complex movement, i.e. it is pressed and rotated, thus simulating motions and loads of a hip joint. For lubricating, 15% polyvinylpyrrolidone was used. During durability and wearing tests, 10 000 cycles were applied upon the load of 400 N. 10,000 cycles have been used in the initial experiments. Actually, a person makes such amount of cycles a day. These tests also showed that some surfaces are not suitable for further research. The testing has been accomplished at room temperature. Each test has been repeated three times. The analysis of variance has been used for statistical evaluation of the test results.

After the wearing tests, the microstructure of the coatings was examined again by a scanning probe microscope. Finally, the analysis of the obtained results was carried out. The coating which has changed little or hasn't changed at all after the friction test has had the highest abrasion resistance.

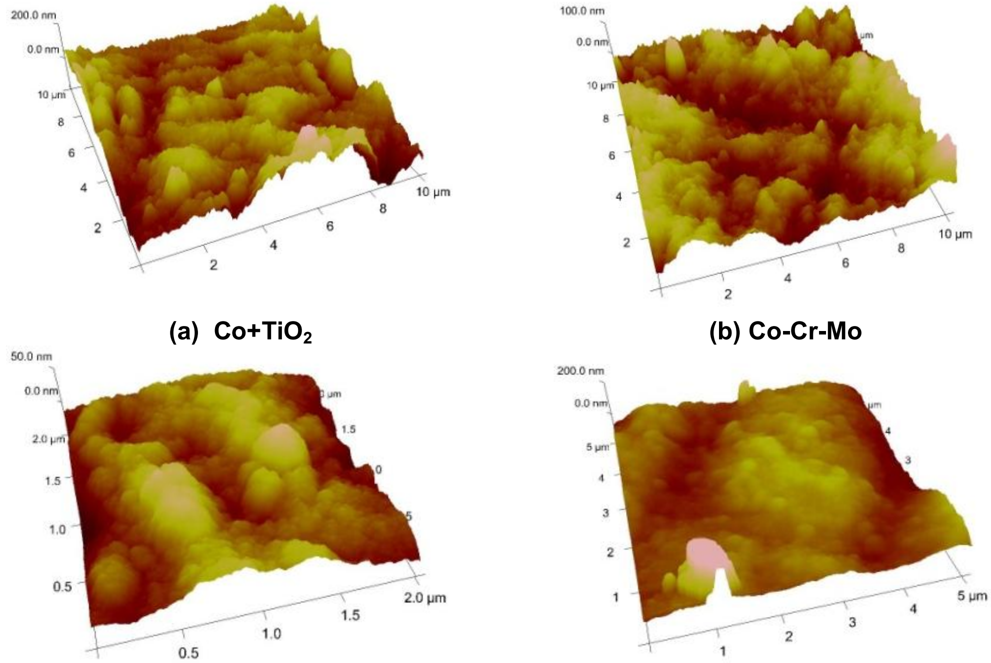
3. RESULTS AND DISCUSSION

Magnetron sputtering method was chosen, since the application of coatings takes place at 70ºC, and by the application of this method properties of polyethylene do not change (its melting temperature varies between 144ºC and 152ºC). Magnetron sputtering technology is characterized in this way: oxide coatings which can be sputtered (reactive sputtering), excellent layer uniformity, very smooth sputtered coatings (no droplets). Magnetron sputtering technology has some disadvantages: slow deposition speed and the adhesion of coatings is lower and the density of the sputtered layers may be lower [15].

The results of the tests are provided in Figs. 2 and 3. In Fig. 2 the photos of the microstructure of Co+TiO_2, Co-Cr-Mo, Zr and ZrO_2 coatings applied onto UHMWPE by magnetron sputtering are provided; they were made by a scanning probe microscope before friction tests. In the course of the analysis of SPM surface morphology images (Fig. 2), it was found that the largest agglomerates of granules are formed in Co-Cr-Mo coating (about 2 μm long, 7 μm wide and 10 nm high). The roughness of Zr coating is minimal; however, it includes large agglomerates of granules (1.5 X 1.7 μm). Zirconium is known as a crystal structure comminuting agent and shows particularly good granular structure refinement effect. The roughness of ZrO_2 coating is relatively low (3.2 X 2.5 μm); however, the structure of the coating consists of large granules. Co+TiO_2 coating is of a moderate roughness with 4.5 X 4.5 μm granular agglomerates.

It was found that after coating with Co+TiO_2 the sizes of particles were found to be between 50 nm and 200 nm, creating a rough surface.

The average sizes of particles are provided in Table 1.



(a) $Co+TiO_2$ (b) Co-Cr-Mo

(c) Zr (d) ZrO_2

Fig. 2. SPM surface morphology images before friction test for the coatings; (a) $Co+TiO_2$, (b) Co-Cr-Mo, (c) Zr, and (d) ZrO_2

Table 1. The average mean values of particles sizes (nm). Data are given in Mean±SD

Coatings			
$Co+TiO_2$	**Co-Cr-Mo**	**Zr**	**ZrO_2**
135,9±63,13	58,66±34,19	34,13±18,43	164,96±54,13

On the analysis of the SPM surface morphology images after the tests on friction stand, it was found that $Co+TiO_2$ coating was distinguished for the best mechanical properties, because the changes of its grain and the shape of its granules particles were inconsiderable. The t-test showed that before and after the friction tests a certain statistical difference between the coatings was calculated ($p<0.05$).$Co-TiO_2$ mean values of particles size ±SD after the friction tests has altered the least. ZrO_2 showed the worst wear resistance: it can be seen from the SPM photo that the surface of this material wore to the maximum extent. Moreover, the amount of ZrO_2 on UHMWPE remained the smallest. After the friction tests, the grain and roughness of the above-described Zr coating increased and the shape of its particles changed considerably. This change was caused by the wear of the coating. Zr and ZrO_2 coatings after the friction tests changed the most significantly (Table 1 and Table 2). The shape of particles in Zr and Co-Cr-Mo coatings became rounded because the sharp inequalities abraded on traction.

The average sizes of particles after friction test are provided in Table 2.

After comparing SPM surface morphology images of coatings prior to the friction tests and after them and the statistical evaluation, we can state that $Co+TiO_2$ coating has demonstrated the best durability and the highest abrasion resistance. $Co-TiO_2$ mean values of particles size ±SD after the friction tests has altered the least. The results of the test showed that the adhesion of the majority of coatings to polyethylene was insufficient and the coatings were worn out soon. This fact shows that prior to application of coating onto polyethylene its surface should be duly prepared and modified to change its hydrophilic and adhesive properties.

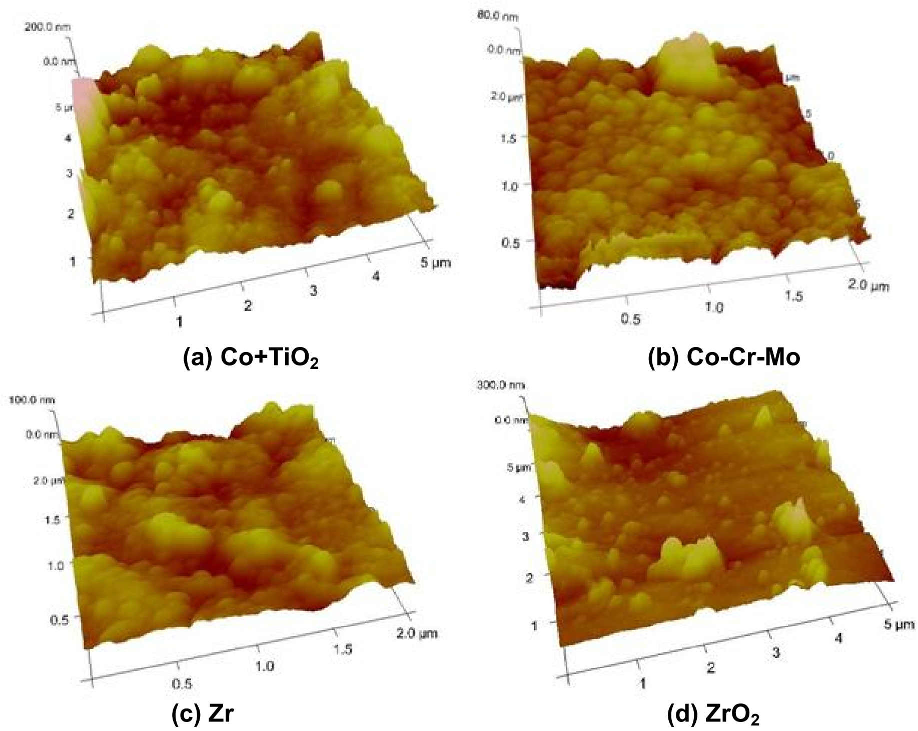


Fig. 3. SPM surface morphology images after friction test for the coatings; (a) Co+TiO_2, (b) Co-Cr-Mo, (c) Zr, and (d) ZrO_2

Table 2. The average mean values of particles sizes (nm) after the completed friction test. Data are given in Mean±SD

Coatings			
Co+TiO_2	**Co-Cr-Mo**	**Zr**	**ZrO_2**
139,6±64,02	62,22±28,56	74,9±37,27	200,56±46,01

4. CONCLUSION

1. UHMWPE causes problems related to the operational life of components of the hip joint prosthesis.
2. The durability and the service life of coatings applied by magnetron sputtering are different for various combinations of metal and ceramic coatings. UHMWPE with Co+TiO_2 coating have demonstrated the best durability and the highest abrasion resistance.
3. During the experiment, the vast majority of coatings have wore considerably. This circumstance may cause the formation of favorable conditions for accumulation of worn out granules around the implant. The application of the coatings of other materials onto polyethylene requires deeper investigation.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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