

K. Zasińska¹, T. Seramak¹, J. Łubiński²

¹*Gdansk University of Technology, Faculty of Mechanical Engineering, Department of Materials and Welding Engineering, Gdansk, Poland
kzasinska@gmail.com*

²*Gdansk University of Technology, Faculty of Mechanical Engineering, Department of Machine Design and Automotive Technology, Gdansk, Poland*

THE DETERMINATION OF ABRASION RESISTANCE OF SELECTED BIOMATERIALS FOR THE FRICTION PAIRS IN THE HIP JOINT ENDOPROSTHESIS

ABSTRACT

The key requirement for the modern endoprosthesis is high durability of the friction components, which results in long and trouble-free operation in the human body. The durability of currently used endoprosthesis is often limited by tribological wear processes of friction components (e.g. between the head and the acetabular component in a hip joint endoprosthesis) [8, 19, 23, 24]. In order to compare the tribological wear, tribological tests were carried out by means of tribometer on friction pairs of the following composition: implantation steel 316 LVM/PE-UHMW and titanium alloy Ti13Nb13Zr/PE-UHMW. Determining of the friction coefficient, measured profiles of surface roughness and microscopic observation allowed to evaluate the abrasive wear of the tested biomaterials.

Key words: *abrasive wear, biomaterials, endoprosthesis, titanium alloys, hip joint*

INTRODUCTION

The head and the acetabular component is the intended friction node of a properly implanted hip joint endoprosthesis. Currently, the main biomaterials for manufacturing friction components of hip joint endoprosthesis are titanium alloys, cobalt alloys, austenitic stainless steels, corundum ceramics and ultra-high molecular weight polyethylene [5]. Titanium and its alloys are at present the most desirable for biomedical uses. In view of the adverse effects on the cells of a living organism of vanadium (V) and aluminum (Al), which are present in chemical composition of Ti6Al4V alloy, the current research aims to eliminate these elements from bioalloys by replacing them with the zirconium (Zr), niobium (Nb), tantalum (Ta), molybdenum (Mo) and platinum (Pt) [1, 2, 3, 16, 17, 23].

The selection of materials on the friction components "head and acetabular " hip joint endoprosthesis significantly affects the life of the implant.

Titanium alloy Ti13Nb13Zr is a preferred biomaterial on long-term implants. Therefore the use of the new generation Ti13Nb13Zr titanium alloy, free of toxic elements, for the endoprosthesis components has been proposed [6].

Tribological tests were carried out in order to estimate the abrasive wear titanium alloy Ti13Nb13Zr in terms of application for the friction pairs in hip joint endoprosthesis.

EXPERIMENTAL

Materials

For tribological tests two metallic biomaterials were used: implantation stainless steel (316 LVM) and titanium alloy (Ti13Nb13Zr) - in combination with sample made of ultra-high molecular weight polyethylene PE-UHMW.

A stainless steel type 316 LVM (low carbon vacuum melted) is an austenitic stainless steel for implants. It belongs to the group of metallic biomaterials, which was adapted to be implanted in the human body at the earliest. The steel 316 LVM, regarded as a medical grade, is characterized by low impurities contents by means of a vacuum melting technology [6, 13, 14]. It has excellent resistance to both general and intergranular corrosion, and pitting and crevice corrosion. The vacuum melt allows for superior surface finish. Beyond removing impurities, vacuum melting, in combination with the unique nickel and chromium content in 316 LVM, tend to facilitate the formation of the surface chromium oxide layer that makes stainless steel corrosion resistant and probably plays a strong role in protecting the host body from reactions to the nickel content of the material. A austenitic stainless steel 316 LVM and 316 L are a common choice of material for the manufacturing components of the hip joint endoprosthesis or other biomedical implants [4]. Ti13Nb13Zr alloy is classified as material belonging to a group of titanium alloys of single β -phase structure. The Ti13Nb13Zr alloy has high biotolerance in combination with the good mechanical properties (high strength, high fatigue strength), high corrosion resistance and has no toxic alloy additives [21, 22]. The tested Ti13Nb13Zr alloy has a low elastic modulus (79 GPa) – this is the most important feature of the usefulness of the alloy for orthopaedic applications. It has an elastic modulus that is very close to the cortical bone (20-30 GPa). Low elastic modulus provides normal stress distribution on the border implant/bone tissue what allows to avoid implant overload and implant loosening and damage in consequence [7, 9, 10].

For many years, the ultra-high molecular weight polyethylene PE-UHMW has been a popular polymeric material used for the manufacturing of friction components of the hip joint endoprosthesis [1, 11].

The chemical composition of a selected biomaterials is given in Table 1.

Table 1. Chemical compositions of tested biomaterials, in wt% [9, 14]

Material	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N	Fe	Nb	Zr	O	Ti
316 LVM	<0.024	0.57	1.7	<0.025	<0.003	17.4	13.6	2.8	0.1	<0.095	bal.	-	-	-	-
Ti13Nb13Zr	0.04	-	-	-	-	-	-	-	-	0.019	0.05	13	13	0.11	bal.

Samples preparation

For the tribological tests, the cylindrical samples with the diameter of 22 mm and the height of 15 mm made of the Ti13Nb13Zr alloy, 316 LVM steel and PE-UHMW were prepared. In all samples the axial holes were drilled. On the end faces of all samples were made circumferential grooves and in addition, on the end faces of the polyethylene specimens the additional radial grooves were made. The axial holes, a circumferential and radial grooves were made in order to improve lubricant transport to the friction zone. In Fig. 1 the shapes and dimensions of the samples used during the tribological tests have been presented.

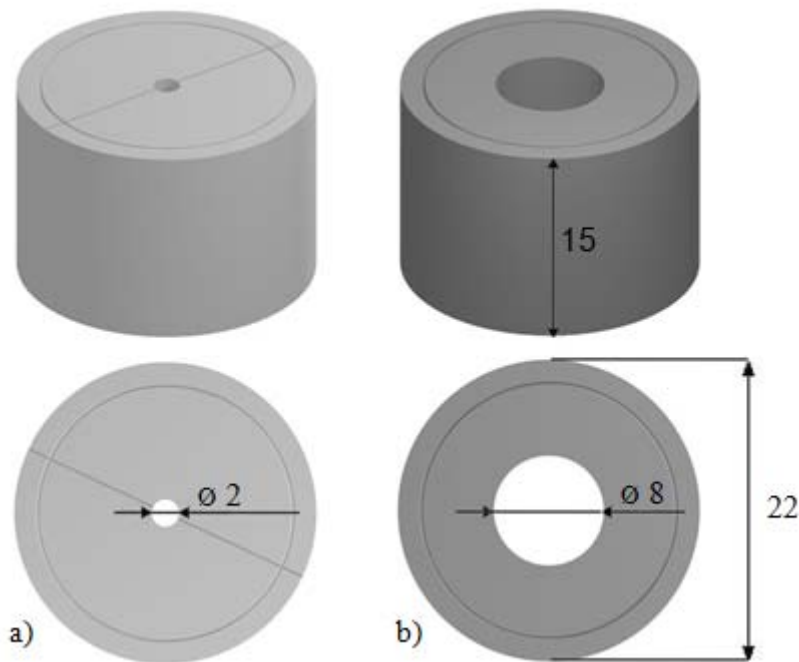


Fig. 1. The shape and dimensions of the samples used during the tribological tests:
a) a sample made of the polyethylene (PE-UHMW), b) a sample made of metallic biomaterials
(steel 316 LVM; Ti13Nb13Zr alloy)

The end faces of the cylinders were machined in compliance with the guidelines defined by ASTM standard No F732-00 in order to obtain their final roughness of $R_a \leq 0.05 \mu\text{m}$. The samples for the tribological tests were ground and polished by means of a grinding and polishing machines with use of sandpaper of grit from 600 up to 3000 and a very fine ($1 \mu\text{m}$) diamond polishing paste. After the final machining, the roughness R_a of samples end faces was obtained in the range of $0.02 \div 0.04 \mu\text{m}$.

Before the tests the polyethylene samples were conditioned in distilled water for 48 hours and dried for 30 minutes at room temperature with the guidelines defined by ASTM standard No F732-00.

Prior to wear tests with the tribometer the quality of the final machining of specimens end faces were observed by means of a light microscope (LM) as well as the profiles of roughness on samples friction surfaces were measured.

Tribological tests

In order to compare the abrasive wear each of tested biomaterials, the tribological tests on friction pairs of the following sets of materials were carried out: implantation steel 316 LVM/PE-UHMW and titanium alloy Ti13Nb13Zr/PE-UHMW.

Tribological tests were also carried out in order to estimate the abrasive wear of titanium alloy Ti13Nb13Zr in terms of its application for the friction pairs in hip joint endoprosthesis.

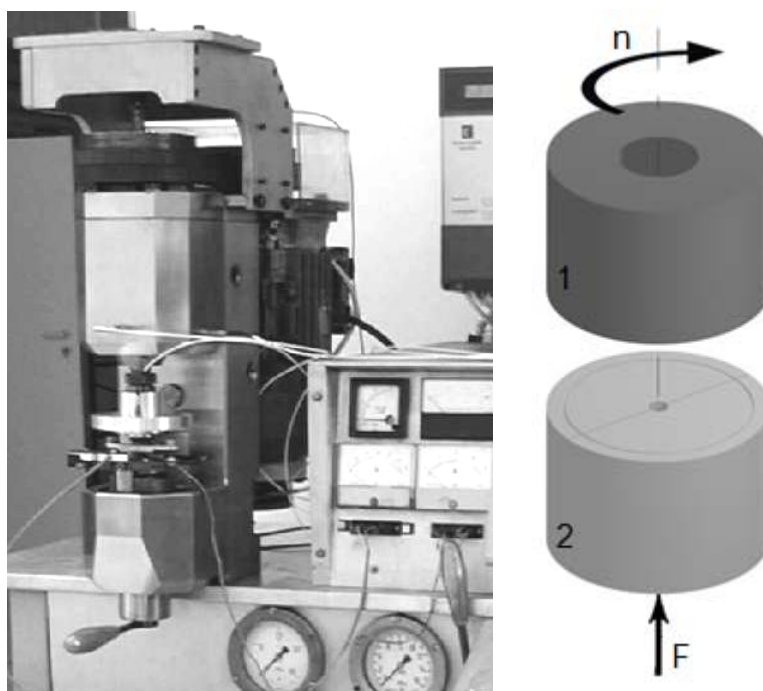


Fig. 2. A view of tribometer PT-3 and the 3D model of investigated friction node:
1) an active sample (rotating) – made of metallic biomaterials (steel 316 LVM, alloy Ti13Nb13Zr),
2) a passive sample (fixed) - polyethylene (PE-UHMW)

The tests were conducted by means of the PT-3 tribometer. Tribometer PT-3 is a universal machine for the study of friction and wear of materials. In the tests described it was configured for ring – on – ring unidirectional sliding tests. The investigated model of friction node consists of two samples - No 1 and No 2. The active sample No 1, made of the Ti13Nb13Zr alloy or 316 LVM steel was fixed to the upper chuck and was set into rotational motion. The passive sample No 2 made of the polyethylene was fixed to the lower chuck. [12, 25].

In Fig. 2 tribometer PT-3 and the investigated 3D models of friction node used during the wear tests have been presented.

The contact patch in the hip joint endoprosthesis was defined as the area of contact between the head and the acetabular component. In order to reflect the type of surface contact between the head of the prosthesis and the acetabulum of the hip - to tests by means of PT-3 tribometer the macro geometry of contact of the flat ring surface of the metal sample with the flat ring surface of polyethylene counter sample was adopted.

The test parameters of abrasive wear were chosen on the basis of literature analysis and the previous research [4, 11, 15, 18, 20] and are shown in Table 2. The total test duration was

divided into time intervals: 3.0, 10.0, 30.0, 60.0, 120.0 and 180.0 minutes. For each adopted load a minimum of the triple repetition of the test was assumed.

Table 2. *The test parameters adopted for the wear tests*

Friction pair	Constant load [MPa]	Rotation speed of the metallic specimens [rev/min]	Test total time [min]
316 LVM/ PE-UHMW	4.5	10	403
	6.0		
	8.5		
Ti13Nb13Zr/ PE-UHMW	4.5		
	6.0		
	8.5		

The tests were carried out in Ringer's solution in order to simulate the tribological conditions in the human hip joint.

Wear resistance of the investigated specimens was determined on the basis of the measured friction coefficient, surface roughness and microscopic observation of the investigated specimens.

RESULTS AND DISCUSSION

In order to compare the surface geometric structure of the investigated samples, profiles of surface roughness were measured before, during and after the tribological tests, it allowed to evaluate the estimation in the value changes of the roughness parameter Ra.

In order to compare of abrasive wear of the investigated samples, the profiles of surface roughness were measured over the distance of 1.25 mm. Analysis of the surface geometric structure of the investigated samples was carried by means of a profilographometer type PGM-1C.

On the basis of measurements and analysis of the roughness profiles (Ra) of the investigated samples after the wear tests, the tendency to increase the roughness with the load increase for both of the friction pairs was observed. The results are shown in Fig. 3 and 4.

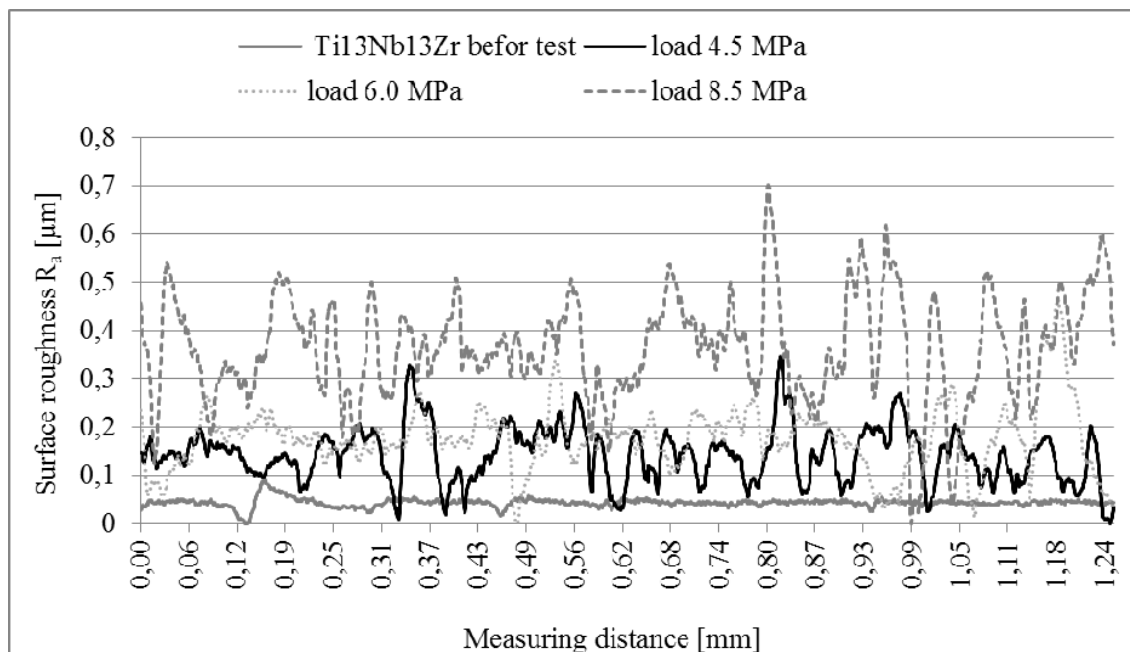


Fig. 3. Profiles of surface roughness of a Ti13Nb13Zr alloy samples after tribological tests at each load

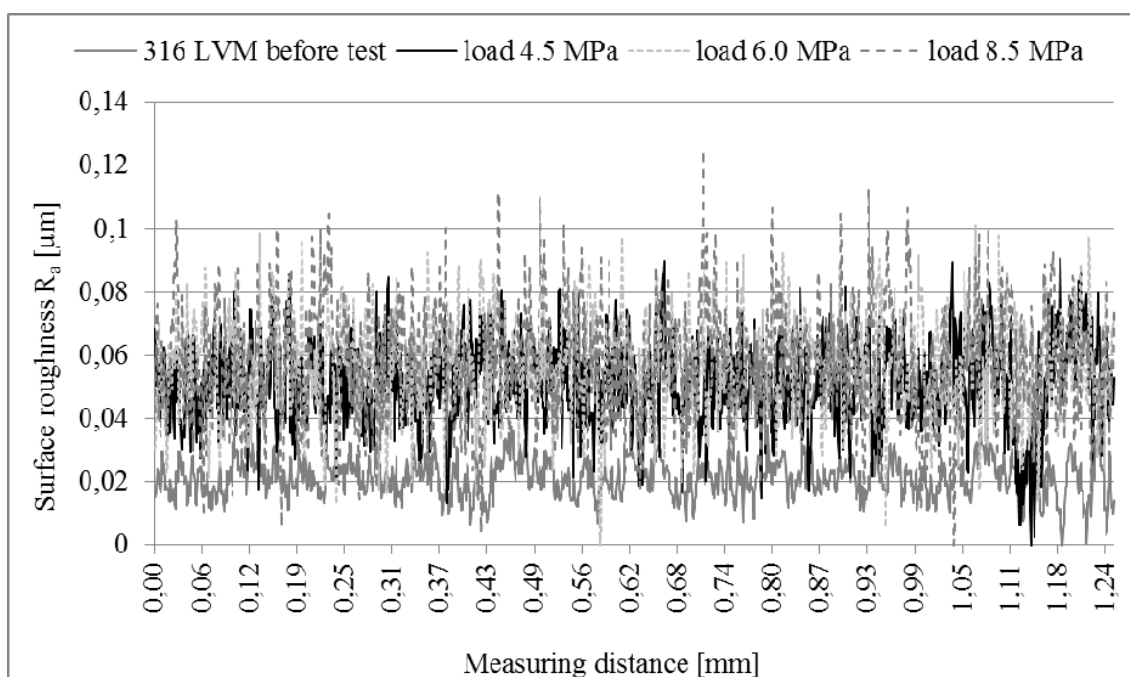


Fig. 4. Profiles of surface roughness of a implantation steel 316 LVM samples after tribological tests at each load

Another observation, regarding the change in roughness of samples end faces after wear tests, is that the increase in the surface roughness is much greater in case of the Ti13Nb13Zr/PE-UHMW friction pair than in the case of 316 LVM/PE-UHMW friction pair.

Surface roughness for the Ti13Nb13Zr alloy is equal to $R_a=0.34$, whilst for the steel 316 LVM is equal to $R_a=0.055$ at maximum load (8.5 MPa). The results are presented in Table 3.

It was observed that for the friction node with the titanium alloy a final value of roughness factor increased up to 7.4 for the metallic specimen and up to 4.3 for the PE-UHMW specimen end face, whereas for the friction pair composed of stainless steel and PE-UHMW these factors are equal to 2.4 and 1.57 respectively.

Table 3. The mean roughness (R_a) of the investigated materials before and after tribological tests (load 8.5 MPa)

Friction pair	Material	R_a before test [μm]	R_a after test [μm]
316 LVM/PE-UHMW	316 LVM	0.023	0.055
	PE-UHMW	0.042	0.066
Ti13Nb13Zr/PE-UHMW	Ti13Nb13Zr	0.046	0.34
	PE-UHMW	0.039	0.168

During the tests carried out by means of the PT-3 tribometer for an assumed load a friction torque was measured, and next a friction coefficient for a tested materials combination (Ti13Nb13Zr/PE-UHMW and 316 LVM/PE-UHMW) was calculated. The friction coefficients were subsequently presented in the form of graphs with the time function for each material combination and the applied load. The calculation results are presented in Fig. 5.

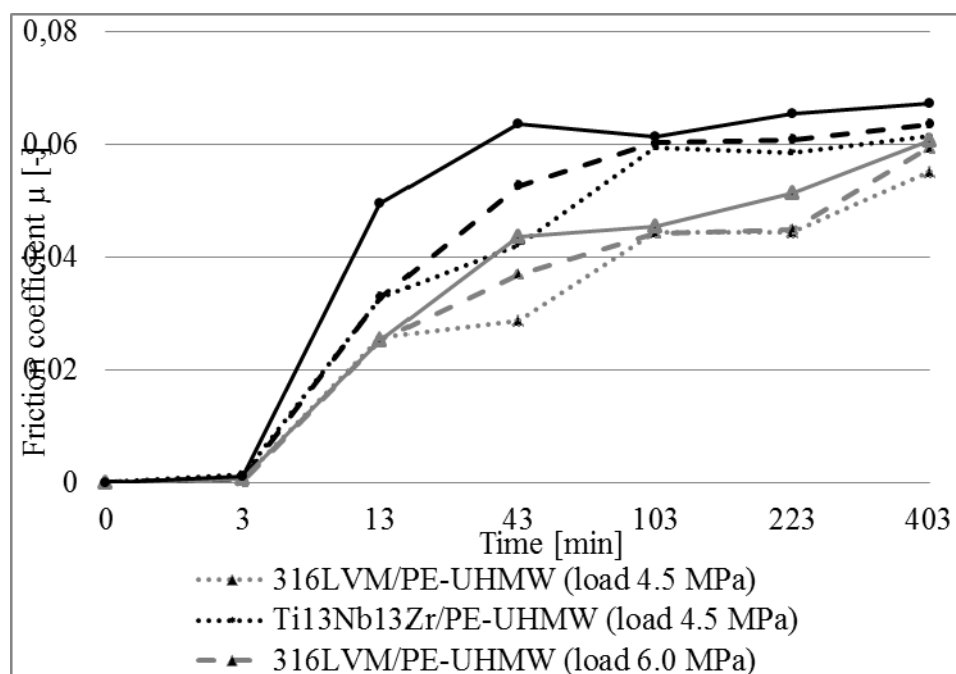


Fig. 5. Friction coefficient of the investigated friction pairs under each applied load

Table 4. Averaged friction coefficient of the investigated friction pairs under each applied load

Friction pair	Constant load [MPa]	The mean friction coefficient μ
316 LVM/PE-UHMW	4.5	0.033
	6.0	0.035
	8.5	0.047
Ti13Nb13Zr/PE-UHMW	4.5	0.043
	6.0	0.045
	8.5	0.061

For both tested friction pairs and for the maximum applied load the similar changes of the friction coefficient in the function of time were observed (Fig. 5). For the combination of Ti13Nb13Zr/PE-UHMW a significantly higher friction coefficient at a given load was observed as compare to the combination of 316 LVM/PE-UHMW (Table 4). For the assumed load range (4.5 ÷ 8.5 MPa) the averaged friction coefficient for the friction pair Ti13Nb13Zr/PE-UHMW ranges $\mu=0.043\div0.061$, whilst for the friction pair 316 LVM/PE-UHMW ranges $\mu=0.033\div0.047$ respectively (Table 4). The tendency to increase the friction coefficient with the load increase for both of the friction pairs was observed.

Materials that are currently used on friction pairs in orthopaedic prostheses are the subject of tribological tests whose aim is to determine the intensity of their wear resistance. The wear resistance tests are based mainly on measurements of the friction coefficient for specified friction pairs. In literature the information on the friction coefficient of the following friction pairs: 316 L/PE-UHMW and Ti6Al4V/PE-UHMW can be found, but it is difficult to find any information on the value of the friction coefficient for the friction pair: Ti13Nb13Zr alloy combined with another material.

In Table 5 values of the friction coefficient of the investigated friction pairs in compare to the values of the friction coefficient obtained by other authors have been presented.

Table 5. Friction coefficient of the investigated friction pairs and the friction coefficient of friction pairs obtained by other authors

Friction pair	The mean friction coefficient μ
316 LVM/PE-UHMW	0.033÷0.047
Ti13Nb13Zr/PE-UHMW	0.043÷0.061
316 L/PE-UHMW	0.061÷0.097 [10] 0.06÷0.13 [14] 0.04÷0.09 [5]
Ti6Al4V/PE-UHMW	0.102÷0.112 [11] 0.016÷0.020 [11, 18] 0.120÷0.150 [4, 13]

The values of the friction coefficient of the investigated friction pairs are comparable with the values of the friction coefficient obtained by other authors.

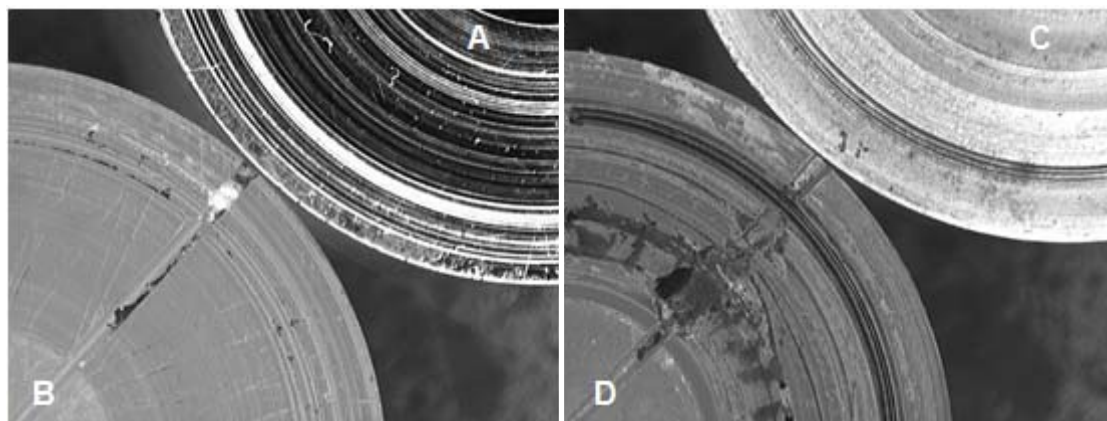


Fig .6. Surfaces of investigated samples after the tribological tests:
 a) 316 LVM, b) PE-UHMW worn in contact with steel 316 LVM,
 c) Ti13Nb13Zr, d) PE-UHMW worn in contact with Ti13Nb13Zr alloy

Based on the microscopic observations the difference in surface change quality of the surface between titanium alloy and stainless steel after wear tests was noticed. Both materials were prepared with identical surface finish, but as result of the conducted tests a much greater degradation of the surface in the case of titanium alloy was observed, which, even at small magnification, was visibly matt after friction (Fig. 6 c). Stainless steel specimen end face was also visibly worn - concentric streaks on highly polished surface were well evident (Fig. 6 a).

In Fig. 6 b and d the significantly higher abrasive surface wear of samples made of polyethylene than for samples made of metallic biomaterials was observed. Significant surface roughness of the metallic material increases abrasive wear polyethylene type soft.

The shown results proved a significantly higher abrasive wear of friction node combined of Ti13Nb13Zr/PE-UHMW than the friction node combined of 316 LVM/PE-UHMW. It seems crucial to try and explain in future tests what is the abrasive wear mechanism of titanium alloy (Ti13Nb13Zr).

CONCLUSIONS

Determining of the friction coefficient, measured profiles of surface roughness and microscopic observation allowed to evaluate the abrasive wear of the tested materials. The results show a significantly higher abrasive wear for the friction combination of Ti13Nb13Zr/PE-UHMW as compared to the friction combination of 316 LVM/PE-UHMW. Despite the advantageous mechanical properties of the tested titanium alloy and its high biocompatibility with the human body, the results show its low resistance to abrasive wear when sliding against PE-UHMW. The tests results do not exclude the feasibility of using the Ti13Nb13Zr alloy for the friction components in hip joint endoprosthesis. Further development is necessary to select technology, which would allow to eliminate the excessive wear problem (also in the polyethylene counterpart) and allow patients to benefit from a minimized or eliminated toxic effect. Further research should include improved surface finish, coatings and surface layer modification (e.g.: ion implantation, hardening in cryogenic conditions, radiation crosslinking, PVD coating, laser treatment, etc.) in order to decrease wear and increase durability and hardness. Currently the

authors are conducting research on the modification of the surface of Ti13Nb13Zr alloy by selected methods. Ti13Nb13Zr alloy is a perspective biomaterial for the friction components in hip joint endoprosthesis.

ACKNOWLEDGMENTS

Authors would like to thank the employees of the laboratory of Department of Machine Design and Automotive Technology and the employees of the laboratory of Department of Materials and Welding Engineering, Faculty of Mechanical Engineering, Gdansk University of Technology for their effort in the realization of the research presented.

REFERENCES

1. Cho H., Wei W., Kao H., Cheng C.: Wear behavior of PE-UHMW sliding on artificial hip arthroplasty materials. *Materials Chemistry and Physics*, 88 (2004), 9-16.
2. Deptuła P., Grądzka-Dahlke M., Dąbrowski J. R.: Investigation of near beta-phase titanium implant alloys produced by the powder metallurgy method [in Polish]. *Inżynieria Materiałowa* 2009/5, (2009), 455-457.
3. Domingo J.: Vanadium and diabetes. What about vanadium toxicity? *Molecular and Cellular Biochemistry* 203 (2000), 185-187.
4. Gierzyńska-Dolna M., Sulej-Chojnacka J., Wiśniewski T., Rybak T.: New materials for knee endoprosthesis pads [in Polish]. *Tribologia*, rok XLI nr 5/2010 (2010), 223-233.
5. Gispert M., Serro A., Colaco R., Saramago B.: Friction and mechanisms in hip prosthesis: Comparison of joint materials behaviour in several lubricants. *Wear* 260 (2006), 149-158.
6. Hermawan H., Ramdan D., Djuansjah J.: Metals for Biomedical Applications. *Biomedical Engineering - From Theory to Applications*. InTech Pub, Croatia (2011), 411-430.
7. Jedynek B., Mierzwińska-Nastalska E.: Titanium – its properties and application in prosthetic dentistry. *Dental Forum, Protetyka Stomatologiczna* 1/2013/XXXXI (2013), 224-233.
8. Koziński C., Trzaskacz T., Ferenc Z.: Tribological properties of degenerate synovial joints [in Polish]. *Tribologia*, XLI nr 4/2010 (2010), 211-222.
9. Krasicka-Cydzik E., Mstowski J., Ciupik F.: Metallic implant materials: implant steel and titanium alloys. *System DERO*, Zielona Góra: LfC (2005), 81-91.
10. Kumar P., Oka M., Ikeuchi K., Shimizu K., Yamamuro T., Okumura H., Kotoura Y.: Low wear rate of PEUHMW against zirconia ceramic (Y-PSZ) in comparison to alumina ceramic and SUS 316L alloy. *Journal of Biomedical Materials Research*, Volume 25, Issue 7, (1991), 813-828.
11. Li X., Dong H., Shi W.: New insights into wear of Ti6Al4V by ultra-high molecular weight polyethylene under water lubricated conditions. *Wear* 250, (2001), 553-560.
12. Łubiński J., Olszewski H., Olszewski A.: A multi-mass discrete model of tribometer for the research on dynamic friction characteristics. *Tribologia*, XLI, 6/2010 (2010), 69-78.



13. Marciniak J.: Biomaterials in bone surgery [in Polish]. Wydawnictwo Politechniki Śląskiej, Gliwice (1992).
14. Marciniak J.: Biomaterials [in Polish]. Wydawnictwo Politechniki Śląskiej, Gliwice (2002).
15. Morlock M., Schneider E., Bluhm A., Vollmer M., Bergmann G., Müller V., Honl M.: Duration and frequency of everyday activities in total hip patients. *Journal of Biomechanics* 34 (2001), 873-881.
16. Munuera C., Matzelle T., Kruse N. at all.: Surface elastic properties of Ti alloys modified for medical implants: A force spectroscopy study, *Acta Biomaterialia* 3 (2007), 113-119.
17. Okazaki Y.: Ito: New Ti alloy without Al and V for medical implants, *Advanced Engineering Materials*, Volume 2, Issue 5 (2000), 278-281.
18. Pawelec Z., Molenda J., Wolszczak M.: Abrasive wear resistance of metal-polymer composites [in Polish]. *Tribologia*, XLI nr 5/2010 (2010), 117-130.
19. Pawlak Z., Jurvelin J., Urbaniak W.: Biotribochemistry of the lubrication of natural joints [in Polish]. *Tribologia*, XLI nr 5/2010 (2010), 131-141.
20. Saikko V.: A simulator study of friction in total replacement hip joints. *Proc. Inst. Mech. Engrs*, 206, (1992), 201-211.
21. Seramak T., Serbiński W., Zieliński A.: Porous biomaterial for orthopedic implants based on titanium alloy. *Advances in Materials Science*, Vol. 11, 1 (2011), 27-34.
22. Serbiński W., Zieliński A., Seramak T., Ossowska A., Sobieszczyk S., Supernak M., Majkowska B.: Surface treatment of porous Ti13Nb13Zr alloy for biomedical applications [in Polish]. *Inżynieria Materiałowa* 2012/1 (2012), 6-12.
23. Wendland J., Gierzyńska-Dolna M., Rybak T., Wiśniewski T., Rajchel B.: Investigation for a new biomaterial for the hip endoprostheses elements [in Polish]. *Obróbka Plastyczna Metali*, XX, 2 (2009), 1-17.
24. Wendland J., Wiśniewski T., Rybak T., Gierzyńska-Dolna M.: Preliminary research on new solutions concerning biomaterials used for endoprostheses' friction elements [in Polish]. *Obróbka Plastyczna Metali* XIX, 1 (2008), 1-5.
25. <http://www.tribologia.eu/ptt/inst/polGdanKoEksMa.htm>