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Modeling and computing of stress and strain distribution in UHMW polyethylene elements of chosen artificial human joints

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The aim of the study was to present numerical strength analysis of the virtual knee and hip joints for the most popular tribological pairs used in prosthetic arthroplasty based on the Finite Elements Method. FEM makes it possible to calculate the stress in particular elements of the tested models. The research was dedicated to elucidate abrasive wear mechanisms during surface grinding of a polyethylene UHMW and a metal elements of endoprostheses. Strong adhesion was found between the abrasives and workpieces, which might be attributed to the chemical bonding between the abrasives and workpieces in synovial liquid. Therefore, the wear of UHMWPE is both chemical and physical. Abrasive wear effect, as a result of the abrasive wear process, is associated with material loss of the element surface layer due to the separation of particles by fissuring, stretching, or micro-cutting.

Keywords: UHMW polyethylene, knee and hip joint endoprostheses, FEM, abrasive wear, tribo-chemical wear.

INTRODUCTION

The solutions used currently in endoprostheses have focused on individual choice of the implant to suit the needs of a patient. The simplest solution is to use a modular endoprosthesis. Apart from numerous opportunities for individualization, this solution prevents from future revision joint surgeries.

It is currently very popular to offer hip endoprostheses with a replaceable cup within metal casing. This solution decreases the operating area that the patient has to be subjected to when the endoprosthesis' parts get worn. The cups and casing are most commonly made of the alloy Ti6Al4V and of an appropriate insert. The replaceable internal element can be made of UHMW-PE, bio-ceramics or – like in the most recent solutions – double-layer materials[1, 2, 3].

At the initial stage of the endoprosthesis design, analytical solutions shall be used to indicate the areas where damages or premature wear of the components may occur. Most of mechanical damages in hip joint replacements are due to fatigue of the material. All the presented numerical computations define valuable conclusions concerning the effect of selected functional parameters on the level of stresses and strains in individual components of the endoprosthesis[4, 5, 6].

The analyses performed in the study revealed that the polyethylene insert represents the weakest component of the endoprosthesis. The presented numerical analysis is the most efficient and clearest method to define distribution of stresses and strains occurring in components of hip and knee joint endoprostheses. Finite Elements Method (FEM) makes it possible to conduct wide range of numerical analysis of strength with the usage of virtual models. As the method provides much more precise results than any simplified analytic calculations, it is commonly used in engineering calculations. The method is not only cheaper and easier than other experimental methods, but is also faster in obtaining results, what is critical in any real conditions. With FEM it is possible to define the values of stress in friction nodes of knee joint endoprostheses, regardless of the shape of sleds or polyethylene inserts, subjected to different loads. Therefore the stress and strain values distribution is clear and obtained quickly, even if there are many similar models of endoprostheses considered, without necessity to bear costs of constructing each of them separately; furthermore it can quickly optimize construction[7, 8, 9, 10, 11, 12, 13]. This paper also aims at explaining the chemical effect on the wear deformation in mono-crystalline polyethylene UHMW components under load sliding. Using of various microscopy techniques and theoretical modeling, it shows that two-body and three-body contact sliding processes yield the same mechanism of sub-surface damage.

POLYETHYLENE UHMW INSERTS APPLIED IN KNEE JOINT EDOPROTHESES

Properly adjusted joints' elements, like sleds and polyethylene inserts, can significantly reduce the problem of high contact stress in the area where the components are subjected to friction and wear. As polyethylene has lower strength values than titanium alloy, the shape of inserts must ensure the reduction of wear. However the perfect shape is till searched for and worked on, as the geometry of polyethylene insert must be optimal in order to prolong the time between implantation and next surgery. There are two kinds of currently used inserts: flat and spherical. It is still widely discussed what would be the best shape for polyethylene inserts used in endoprostheses, as far as functional, assembly and strength features are concerned, as those are critical for the endoprosthesis durability[14, 15]. Some constructors and medical doctors support the option of flat inserts, as those allow some surgical mistakes during implantation of both elements of endoprosthesis. Spherical inserts adherents emphasize that thanks to this shape, the range of unit pressure is acceptably low; but they also admit, that implanting this kind of insert requires accuracy and precision[16, 17, 18, 19].

KNEE JOINT ENDOPROTHESIS BY W.LINK

The Figure 1 presents the product by W. Link, which is an example of knee joint endoprosthesis. The femoral part copies the shape of condyles of femur bones.

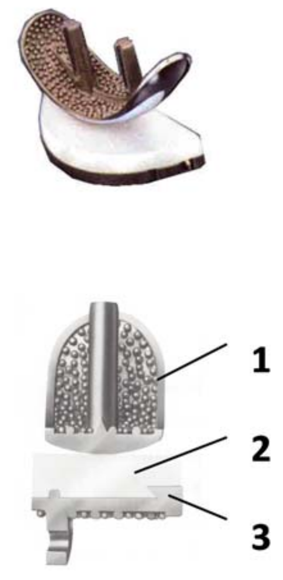


Figure 1. Knee joint endoprosthesis by W.LINK, 1 – metal sled, 2 – polyethylene UHMW insert, 3 – metal tibia part[20]

GEOMETRICAL MODEL OF KNEE JOINT ENDOPROTHESIS

Considering a very simple wear model[21, 22, 23], numerical analysis of tribological phenomena taking place in artificial joints, reveals the wear process of UHMWPE polyethylene insert, used in knee joint endoprostheses. If we want to analyse contact strength or stress occurring in flat polyethylene insert, it is enough to construct simplified model consisting of metal sled and polyethylene insert, what will let us settle the required values and analyse the phenomena occurring in the friction point of endoprosthesis.

The analysis was carried out in ADINA System 7.5.1. based on finite elements method. The finite elements mesh was built of 3600 cube-shaped elements of 3D Solid type and 4312 nodes. The model presented in the paper, consists of the elements respective to all parts of endoprosthesis. Additionally, there are presented numerical calculations defining the influence of the implant geometry on the stress pattern in the contact area of the cases: sled with the cross section radius 17 mm – spherical insert and sled with the cross section radius 27 mm – spherical insert. Geometrical model of sled – spherical insert subjected to load and finite elements mesh is shown in Figure 2. Such a discrete model of sled and insert was used to simulate the performance of polyethylene inserts subjected to mechanical loads.

The main purpose of the calculations was to define stress distribution on the surface of the polyethylene insert and right underneath it, where the sleds cooperate. The analyzed sleds were made of CoCrMo, Ti6Al4V, Ti13Nb13Zr, Ti12Mo6Zr2Fe, TiNbZrTa. Figure 3 presents sleds' geometry of the analyzed knee joint endoprosthesis.

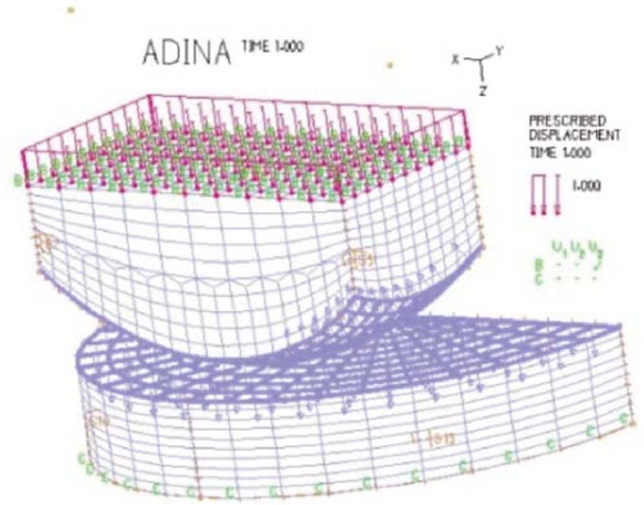


Figure 2. Geometrical model of the set sled – flat polyethylene insert. Finite elements mesh, load, degrees of freedom and contact area. General view

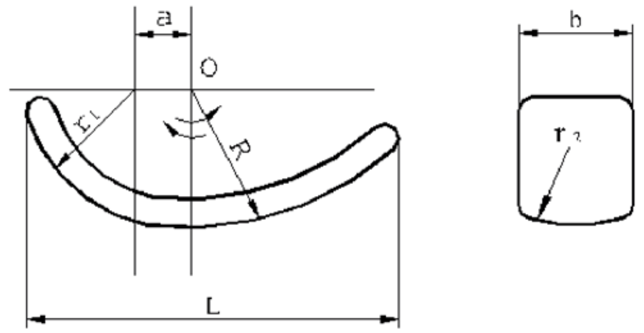


Figure 3. Knee joint endoprosthesis sled's geometry. Side and front view

Sleds' geometric value, accepted as a specific parameter, defined cross-section radius of a sled. Constant geometric diameters are:

Sled of geometry: R = 28 mm; r_1 = 15 mm; r_2 = 27 mm; L = 46 mm; b = 17,5 mm

Sled of geometry: R = 26 mm; r_1 = 16 mm; r_2 = 17 mm; L = 45 mm; b = 16 mm

There were conducted 30 numerical analysis for three various thicknesses of polyethylene inserts cooperating with two geometrically different sleds made of five different alloys. Each pair was subjected to load F = 1500 [N]. Simulations of the cases were conducted with the following, accepted physical features of the materials are presented in Table 1.

Table 1. Mechanical features and weight density of the materials used for endoprostheses[24]

	Young's modulus E [GPa]	Poisson's coefficient ν	Weight density ρ[kg/m^3]
CoCrMo	210	0.29	8300
Ti6Al4V	110	0.3	4500
Ti13Nb13Zr	80	0.3	4510
Ti12Mo6Zr2Fe	73	0.3	4510
TiNbZrTa	53	0.3	4490
UHMWPE	0.01	0.4	960

There were conducted 30 numerical analysis for polyethylene inserts cooperating with two geometrically different sleds made of five different alloys. Each pair was subjected to load F = 1500[N]. Stress distribution in the contact area, where the sleds are pressed onto the inserts, are based on the assumptions:

– the contact area is continuous and relatively smaller than other cooperating elements,

– implemented load is close and relative to the one occurring in the real knee joint,

– both contacted parts are made of isotropic material and obey Hook's law.

Boundary conditions, settled for the calculations represent mechanical features of endoprostheses' elements as well as mechanical load distribution and values. It was assumed, that all materials used for models (medical titanium alloys, polyethylene UHMWPE) are linear-elastic and isotropic with constant mechanical features.

THE RESULTS OF NUMERICAL ANALYSIS CONDUCTED WITH THE USE OF FINITE ELEMENTS METHOD AND ADINA SYSTEM 8.6.

The calculations prove that stress in endoprosthesis is concentrated in the polyethylene insert, right underneath the contact area of both elements, and highest stress is located right underneath the insert's surface. Some examples of the calculations are presented in Figures 4 and 5.

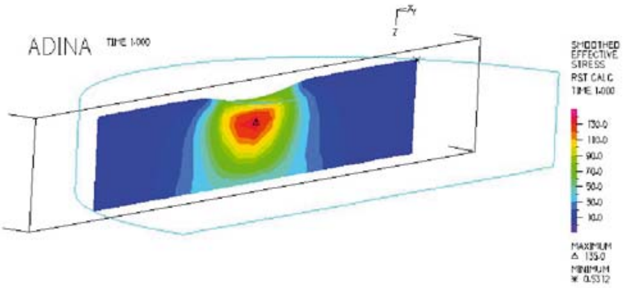


Figure 4. Contact stress distribution occurring in a flat polyethylene insert. Flat insert 8 mm thick cooperates with a sled of radius 17 [mm]. Load 1500 [N]

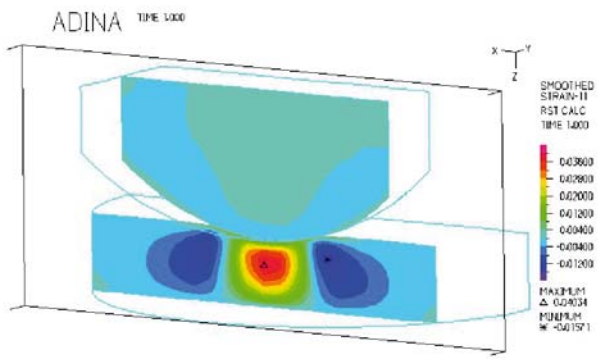
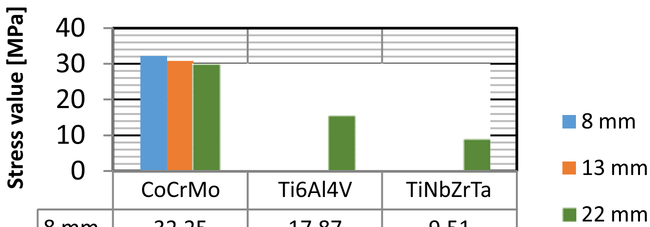


Figure 5. Strain distribution occurring in flat polyethylene insert. Flat insert 8 mm thick, cooperates with sled of radius 27 [mm]. Load 1500 [N]

TESTS RESULTS AND CALCULATIONS REMARKS

Using sled with cross – section radius = 27 mm, the reduced stress was most decreased, while the highest was for sled of cross – section radius = 17 mm.

Figure 6 presents how the cross section radius of the sled, thickness of the insert and used affect the value of the stress generated in the flat polyethylene insert.



	CoCrMo	Ti6Al4V	TiNbZrTa
8 mm	32,25	17,87	9,51
13 mm	30,85	15,94	9,12
22 mm	29,78	15,45	8,88

Figure 6. The influence of the sled's cross section radius and insert's thickness on the value of the stress generated in the flat UHMWPE insert

The conducted numerical calculations and analysis prove that the future of knee joint replacement belongs to a group of new materials including titanium alloys, which when appropriately selected and combined as far as mechanical features are concerned (low Young's modulus value), may significantly decrease the value of stress generated in polyethylene elements of endoprostheses.

Another important element influencing durability of endoprostheses is optimizing of the geometry of the implants both in the friction node and fixing area in the bone.

NUMERICAL ANALYSIS OF THE LOAD TO THE MODULAR HIP JOINT ENDOPROTHESIS

The geometrical model of the endoprosthesis was developed using the Autodesk Inventor 2017 software. It represents a modification of real endoprosthesis manufactured by Zimmer[25]. The model is composed of seven basic parts. The endoprosthesis is composed of the stem (distal and proximal) fixed by means of a lock screw, titanium or ceramic head, acetabulum, and the acetabulum housing. The materials used for individual parts were chosen based on the literature data[26, 27] and generally adopted solutions used for implantation of endoprostheses:

– stem (distal and proximal) made of Ti6Al4V,
– endoprosthesis head: Ti6Al4V or ZrO_2
– internal acetabulum: UHMWPE,
– acetabulum housing: Ti6Al4V,
– self-tapping bone screws: Ti6Al4V,
– lock screw: Ti6Al4V.

Numerical analysis was performed using the finite element method by means of Autodesk Simulation Mechanical 2017 software. The system of restraints and loads was based on the Będziński's active model, modified and simplified to facilitate simulation. The values of loads were adopted based on the literature data[5, 28, 29]. The loads with the values of 600 N and 750 N, respectively, were applied to the external surface of the endoprosthesis acetabulum housing. Figure 7 illustrates geometrical model of the adopted solution and the surfaces to which the load was applied.

In the area of tribological interaction of the system, the contact was modelled with the option of the head motion with relation to the acetabulum at adopted coefficient of friction. However, the presented static analysis does not concern the solutions in this area. Figure 8 illustrates the example distributions of stress and strain

Figure 7. Surface where the loads were applied

(cross-section of the analysed system) for the pair of the Ti6Al4V head and UHMWPE acetabulum.

The highest values of stress at the load of 600 and 750 N were observed in the endoprosthesis head just at the stem collar, reaching the values of 11 MPa for the loading force of 600 N and 14 MPa for the force of 750

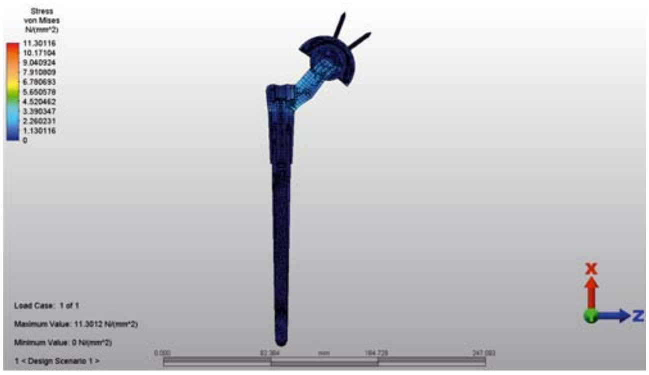


Figure 8. Distribution of stress in the analysed system at the load of 600N. Endoprosthesis head made of Ti6Al4V alloy

N. The change in material pairs, consisting in the use of the endoprosthesis head made of ZrO_2, did not lead to noticeable differences in the results obtained. Maximal stresses for the analysed cases are illustrated in Fig. 9.

As expected, maximal stresses were observed in the acetabulum made of UHMWPE. However, they reached a very low levels and it can be concluded that they do not have an effect on stability of the system.

The analysis performed in the study revealed that the values of stresses and strains in the analyzed system at the adopted load similar to that in natural conditions are low. They do not cause formation of locations with accumulated stresses. Polyethylene components are not exposed to substantial strains, which can be a good predictor of a longer life of these components. The findings of the study lead to the conclusion that the adopted geometrical solutions are optimal and allow for long and failure-free use.

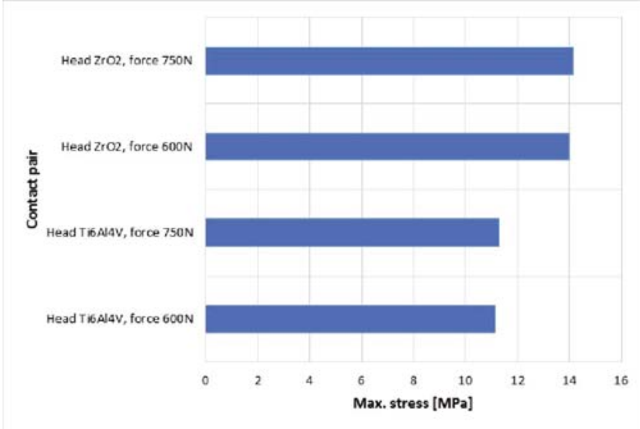


Figure 9. Maximal stresses in the analysed contact pairs

EXPERIMENTAL WEAR TESTING OF FRICTION COMPONENTS OF THE KNEE JOINT ENDOPROSTHESES

Simulator for testing the durability of human knee joint endoprostheses was developed at the Institute of Metal Working and Bioengineering of the Czestochowa University of Technology. The simulator for friction and wear tests meets the following conditions:

– it models the contact geometry of knee joint endoprosthesis being examined,

– it models the kinematics of motion, characteristic of the knee joint

– it allows for obtaining the load to the friction pair of P = (2–5) G, where G is body weight of an average human, adopted as 70 kg

– it allows for the measurement and recording such quantities as: normal load, number of loading cycles, the amount of linear wear of the polyethylene insert and collecting the resulting abrasive wear products. Abrasive wear occurs when a certain material scratches or gouges a softer surface. It has been estimated that abrasion is responsible for 50% of all wear-related failures. A typical example of abrasive wear is the damage of polyethylene parts of knee and hip joint endoprostheses. Hard dirt particles will break through the lubricant film - synovial liquid and cut or scratch the polyethylene parts comparatively softer surface[30, 31, 32]. The wear tests presented in this paper were conducted using the above-mentioned simulator. Figure 10 shows a front view of the station for testing of human knee joint endoprosthesis durability.

The device simulates the working conditions of the bio-bearings in the musculoskeletal system during performance of squats with an additional load. The motion of lower limbs simulated in this way allows for faster tribological examinations of endoprostheses. Furthermore, the movements forced by the simulator are accelerated in relation to human movements. Wear tests of these components under near-real loading conditions is extremely time-consuming. Therefore, some acceleration of the wear process by increasing the unit pressure of the friction pair within certain limits was considered necessary. The test stand enables a smooth hydraulic adjustment of the load to the friction pairs and the angle of flexion of the knee joint endoprosthesis. Therefore, abrasive wear rate is directly proportional to the applied load and inversely proportional to the hardness of the abraded material. It has been also found that abrasive

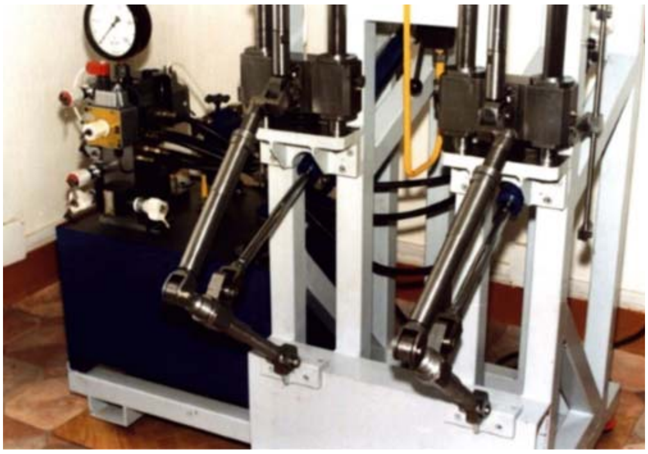


Figure 10. Front view of the stand for testing durability of human knee joint endoprostheses

wear rates depend, to a large extent, on the hardness ratio between the abraded material and the abrasive.

EXAMINATIONS OF CHANGES IN THE DEGREE OF CRYSTALLINITY OF UHMWPE USED FOR KNEE JOINT ENDOPROSTHESIS INSERTS EXPOSED TO THE LOAD

The test parameters evaluated for the W.LINK sled endoprosthesis with a flat insert were as follows:

– normal force load P = 1500 N for the group of samples, maximal flexion angle β = 90º,

– relative velocity of the friction pair v = 0.03 m/s (in the movement test), full cycle of the endoprosthesis movement on the simulator is 0.25 Hz, which corresponds to 15 full cycles/min,

– each set of samples was subjected to 3 million loading cycles and the tests were carried out without the use of lubricant.

The distribution of the loads transferred by the insert is closely related to wear of the respective endoprosthesis component. The abrasive wear of a polyethylene component is directly proportional to the load transferred, which in turn results in specific stress values. It was necessary to determine the method of measuring the amount of wear to evaluate the rate of wear of polyethylene inserts and their susceptibility to wear[16, 17, 18, 19].

Abrasive wear is a very common and, at the same time, very serious type of wear. It arises when two interacting surfaces are in direct physical contact, and one of them is significantly harder than the other just like in case of tribological node of endoprosthesis. As the number of cycles increases, the linear contact becomes a surface contact. With this frictional contact geometry, a wear trace in the form of an elongated ellipse is formed in the first stage of meshing of the friction elements on a polyethylene sample, caused mainly by the plastic deformation (flow) of the element of lower strength, i.e. the polyethylene insert. As the number of cycles increases, the depth and surface area of the deformed region increases and then stabilizes, indicating that as a result of the increase in the actual contact surface, the unit pressure values does not exceed the permissible pressure for this type of material. However, when a certain number of cycles is exceeded, fatigue wear occurs. The amount of permanent plastic deformation of the base material depends on the geometry of the sliding surface of the endoprosthesis sled, the value of the normal force and the time of its application, and above all, on the elastic-plastic properties of the material of the polyethylene UHMW insert.

In order to verify whether, as a result of the friction process observed in the area of the friction pair of the endoprosthesis and the related wear, a change in the degree crystallinity may occur in the surface layer of the material (UHMWPE in this case) it was considered necessary to conduct examinations of the changes in the degree of crystallinity using the NETZSCH DSC 200 PC Phonox device. Differential scanning calorimetry (DSC) was used to perform the tests, with material samples obtained from the places on the polyethylene insert are marked in Figure 11.

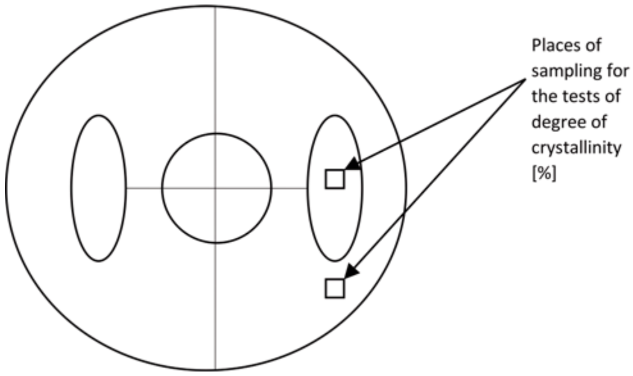


Figure 11. Flat polyethylene insert for knee joint endoprostheses with marked sampling places for the examinations of the degree of crystallinity

Samples were taken from the area where friction processes took place and from the area not affected by the processes of friction and wear of polyethylene inserts. Three samples were taken both from the loading area and from the area outside the sled. The tests were carried out using the following parameters:

– initial heating temperature: 20ºC

– final heating temperature: 195ºC

– heating rate: 10ºC/min

The results of the examinations of the degree of crystallinity for polyethylene inserts exposed to different numbers of loading cycles using the knee joint simulator are presented in Table 2 and shown graphically in Figure 12.

Figure 13 shows how the degree of crystallinity of UHMWPE changes as a function of the number of loading cycles.

Table 2. The results of examinations of the degree of crystallinity

Sample No.	Number of loading cycles	Degree of crystallinity [%]	Mean degree of crystallinity [%]
1	0	56.5	59.466
2	0	58.6	
3	0	63.3	
1	1 million	71.7	71.966
2	1 million	70.7	
3	1 million	73.5	
1	3 million	87.2	85.5
2	3 million	83.8	

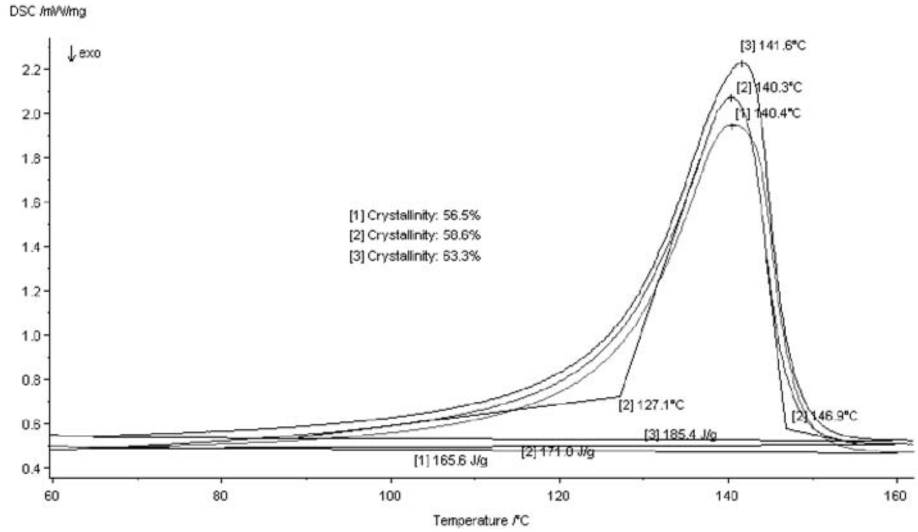


Figure 12. Results of examinations of the degree of crystallinity of non-loaded polyethylene samples

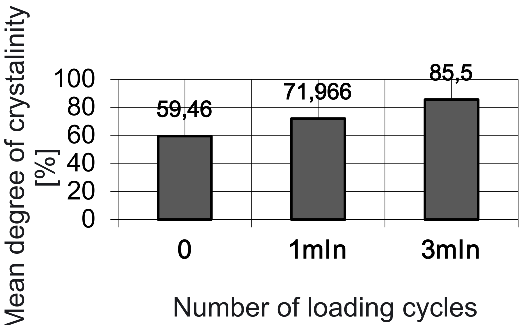


Figure 13. Change in the degree of crystallinity of UHMWPE used in the endoprosthesis insert vs. the number of loading cycles

The examinations showed that variable cyclic frictional load applied to the knee joint simulator causes an increase in the percentage of the crystalline phase α with a simultaneous decrease in the percentage of the amorphous phase ϒ. An increase in the share of the crystalline phase with an increase in the number of loading cycles (and the related increase in the friction distance) results in greater brittleness of the material and susceptibility to micro-crushing. The examinations of changes in the degree of crystallinity of the material due to friction indicate an important problem, i.e. the choice of material for knee joint endoprosthesis inserts in terms of the structure, but they do not solve it[20].

It can be concluded from the measurements that the exposure of the polyethylene insert to the load during the examinations of the endoprosthesis on the knee joint simulator results in an increase in the degree of crystallinity. A mean increase in the degree of crystallinity of polyethylene used in the tests is between 10 and 12% after 1 million cycles and about 13% in the case of 3 million loading cycles compared to the previous state. Observation of these changes leads to the conclusion that with an increasing number of cycles of the load applied to the polyethylene inserts, the brittleness of the material increased in the area of the friction pair. This can lead to the formation of cracks in this area, causing the destruction of the insert surface and thus disturbing the kinematics of the movement of the endoprosthesis. Adhesive contact in a tribological context refers to quasi-instantaneous adhesion between contacting surfaces as a result of van der Waals forces or electron transfer. Adhesion is necessarily a rapid process because periods of contact between asperities in sliding are extremely short. Figure 14 shows a diagram of cross delamination wear of polyethylene insert, subjected to load while tested on knee joint simulator, occurring under roll – slide movement of sled.

Fig. 15 shows graphic presentation of roughness measurement results of polyethylene insert cooperating with sled in friction node of knee joint endoprosthesis.

The abrasive wear is constituted by the interaction between the fluid stream, wherein the abrasive partic-

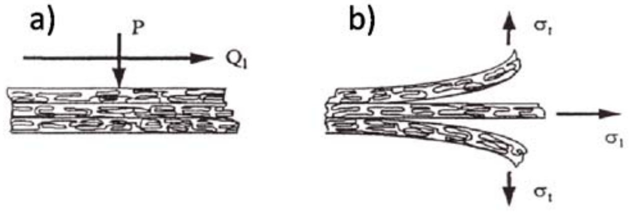


Figure 14. Diagram of cross delamination wear of polyethylene insert: a) cross view, revealing plastic particles distribution, b) surface view, showing cross delamination of polyethylene layers

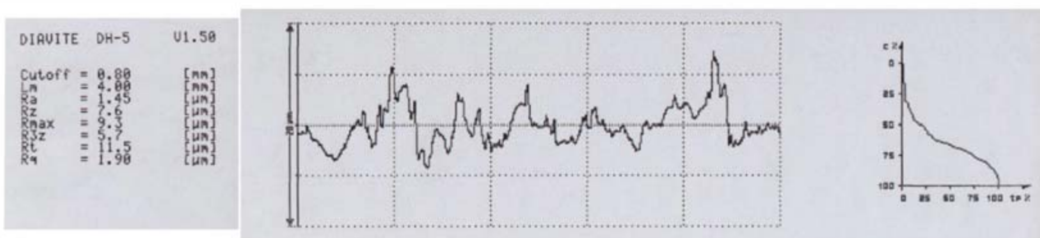


Figure 15. Graphic presentation of roughness measurement results of polyethylene insert cooperating with sled

les are suspended, and metal abrasion in the abrasive environment, where contact between the grains and abraded surface occurs, causing abrasion and crushing the material. Figure 16 shows topography of UHMWPE insert's surface after 3 million cycles on simulator.

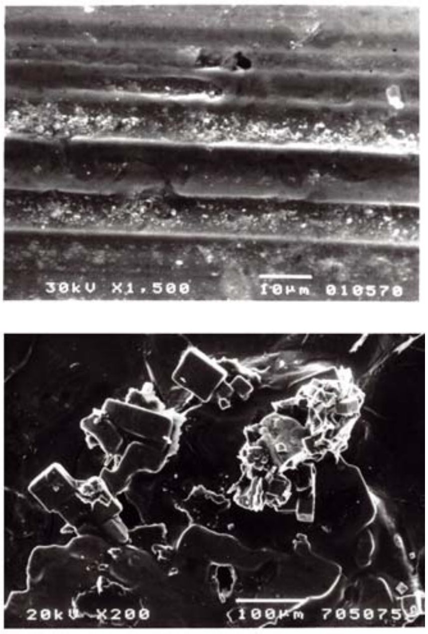


Figure 16. Topography of UHMWPE insert's surface after testing on simulator of human knee joint. Visible micro cracks and exfoliating particles of polyethylene. Scanning microscope, magnification 1000. Load 1500 N

CONCLUSIONS

The conducted numerical calculations and analysis undoubtedly prove that the future of knee joint replacement belongs to a group of new materials including titanium alloys, which – when appropriately selected and combined as far as mechanical features are concerned (low Young's modulus value) – may significantly decrease the value of stress generated in polyethylene elements of endoprostheses.

The analysis performed in the study revealed that the values of stresses and strains in the analysed system submitted to load similar to the one in natural conditions, are low.

Polyethylene UHMW is the weakest point of the endoprosthesis, that is why it is important to present the reduced stress distribution in the inserts and in the cups.

Polyethylene components are not exposed to substantial strains, which can be a good predictor of a longer life of these components. The findings of the study lead to the conclusion that the adopted geometrical solutions are optimal and allow for long and failure-free use.

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For all the sliding conditions studied with load 1500 N, it was found that an amorphous layer always appears and its thickness depends on the sliding load applied, and the extent of chemical reaction. In human joints synovial liquid penetrates the amorphous layer, changes the atomic bonding of UHMW polyethylene, alters the threshold for amorphous transformation and accelerates wear. However, there are still exist a number of problems that require further study.

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