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THE ANALYSIS OF THE INFLUENCE OF STRESS DISTRIBUTION ON WEAR PROFILE IN LUBRICATED SLIDING CONTACT OF UHMW-PE VS TITANIUM Ti-13Nb-13Zr ALLOY

ANALIZA WPŁYWU ROZKŁADU NAPRĘŻEŃ NA PROFIL ZUŻYCIA W SMAROWANYM STYKU ŚLIZGOWYM UHMW-PE ZE STOPEM TYTANU Ti-13Nb-13Zr

Key words: friction of solids; tribological experiment, wear, titanium alloys, endoprosthetic materials.

Abstract: Metal – polymer sliding contacts are a typical combination in industry and medicine. For decades such a set of materials has been the primary choice in human joints endoprosthetic technology. In this paper tribological issues of are presented from a research on the potential for practical use of Ti-13Nb-13Zr/UHMW-PE couple for orthopedic endoprosthesis. In tests on simplified models it is critically important to carefully select geometry of contact, load and velocity magnitudes and profiles to the later interpretation of results. In case of organic polymers interacting with metallic components the problem is even more prominent, than in the case of all metal systems because of great differences in the modulus of elasticity between the specimens in contact. High local loading can cause excessive heat generation and accelerated loss in polymer's strength induced by thermal plastification. The process may not be manifested in the course of the experiment in any way detectable and might compromise the accuracy of wear measurement. In the case of the presented research an analysis has been performed to evaluate the observed wear profile of UHMW-PE with respect to non-uniform distribution of contact stress. A simulation was run with the use of FEM to evaluate the contact conditions between the titanium alloy and UHMW-PE specimens and the results were confronted with the wear profiles. Interesting similarities were discovered yielding useful information on the fundamentals of the wear in and for future research on similar systems.

Słowa kluczowe: tarcie ciał stałych, eksperyment tribologiczny, zużycie, stopy tytanu, materiały na protezy stawów.

Streszczenie: Skojarzenia ślizgowe metalowo-polimerowe są często spotykane w zastosowaniach przemysłowych i medycznych. Od długiego czasu są najczęściej wybierane w technice protez ortopedycznych. W artykule przedstawiono wybrane problemy tribologiczne spotykane w skojarzeniach stopu tytanu Ti-13Nb-13Zr oraz polietylenu UHMW-PE. W przypadku badań na modelach uproszczonych bardzo ważną kwestią jest właściwy dobór geometrii styku, wartości obciążenia i prędkości ślizgania oraz przebiegu zmian tych parametrów wymuszenia. Późniejsza interpretacja wyników i ich przydatność do zastosowań praktycznych jest ściśle związana z tak rozumianym przygotowaniem doświadczenia. W przypadku skojarzeń materiałów polimerowych z metalowymi ważnym czynnikiem wpływającym na skutki tarcia jest różnica w wartościach modułów sprężystości tych dwóch grup materiałów. Duże lokalne obciążenia mogą np. prowadzić do miejscowego przegrzewania powierzchni polimeru i plastyfikacji, co może zmniejszyć wartość uzyskanych wyników. W pracy przedstawiono analizę profilu zużycia próbek UHMW-PE w zależności od rozkładu nacisków powierzchniowych. Zastosowano symulacje z wykorzystaniem MES w celu analizy czynników wpływających na warunki kontaktu próbek ze stopu tytanu i polietylenu UHMW. Uzyskane wyniki symulacji znajdują potwierdzenie w zarejestrowanych doświadczalnie profilach zużycia próbek polimerowych. Zaobserwowano zależność rozkładu nacisków od warunków podparcia i naprężeń montażowych działających na próbkę.

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CONDITIONS OF TESTING

The tests were performed in the PT-3 tribometer **[L. 1-4]** configured for flat-on-flat contact (annular shaped). The arrangement of specimens is presented in **Fig. 1.** Both specimens are cylindrical in shape with the outside diameter equal to 22 mm. Of the two the lower specimen is made of UHMW-PE and is seated in a non-rotating chuck in a self-aligning support equipped with the friction torque measurement system. The upper specimen is manufactured from Ti-13Nb-13Zr alloy. Both specimens were machined to an average roughness Ra<0.06 μm and both have holes machined through the centre to allow for lubricant circulation and to avoid lubricant starvation in the friction zone. The polymer specimen also has radial an circumferential grooving on the working face for lubricant circulation and improved evacuation of wear products from the friction zone.

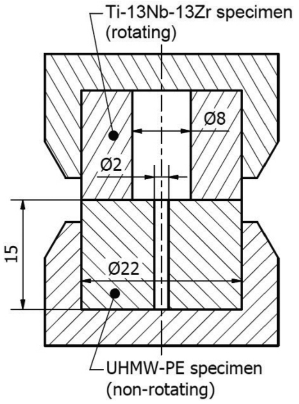

Fig. 1. A schematic view of the experimental set up used in the research

Rys. 2. Widok schematyczny układu próbek użytego w badaniach

The tests were performed at steady state conditions and run in an intermittent mode with the test run broken up into progressively timed intervals of 3, 10, 30, 60, 120 and 180 minutes. At intermissions the specimens were examined by optical methods, profilographometry and weight control. The test conditions are presented in **Table 1**. The sliding contact was immersion lubricated with Ringer solution. The solution drained and refilled at every stopover.

Table 1. The test parameters adopted for the wear tests

Tabela 1. Parametry przyjęte do badań tribologicznych

Load	Rotational velocity	Test time
[kN] ([MPa])	[RPM] ([m/s] – average)	[min]
3,0 (~9)	10 (~0.3)	403

WEAR PROFILE

The basic analysis of wear performed on the tested system was concentrated on loss of material on both sides of the contact and on the degradation of the sliding surface. The performance of endoprosthetic solutions relies heavily on resistance to severe wear which can cause adverse immunological reactions and health problems. The analysis performed was based on typical approach **[L. 6-9]** and fully acceptable from the methodical point of view, but upon more detailed second analysis of the available material an interesting regularity was observed in the way the PU-UHMW specimen was wearing. All the specimens were subjected to profiling along the radius of the working face prior and after testing. An example of such two profiles is shown in **Fig. 2.** The profile before test shows the flat surface with some irregularities resulting from machining and a circumferential groove (design depth of the groove 0.2 mm) – wear depth marker. In the second profile the cross section of the wear thrack is clearly visible with some material build up near the centre of the specimen (left side of the plot) and a clearly visible diminishing of the circumferential groove depth. Both the roughness and waviness of the working surface are clearly degraded as a consequence of the test run. Apart from these features a distinct convex profile of the worn surface near the mid-section of the profile. The wear profile was almost identical on all specimens used so the case was analysed with respect to input parameters and a simulation was performed in order to study the distribution of load on the contact surface.

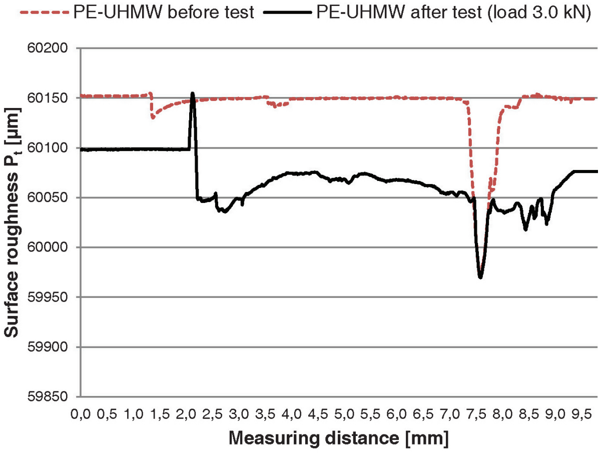

Fig. 2. Radial profile from the working face of a PE-UHMW specimen before and after testing.

Rys. 2. Profil promieniowy czoła roboczego próbki z PE-UHMW przed i po badaniach

CONTACT STRESS DISTRIBUTION SIMULATION BY FEM

Both specimens are friction gripped in cylindrical chucks **(Fig. 1)**, which provide a good flat support on the unused face of the specimen and circumferential radial

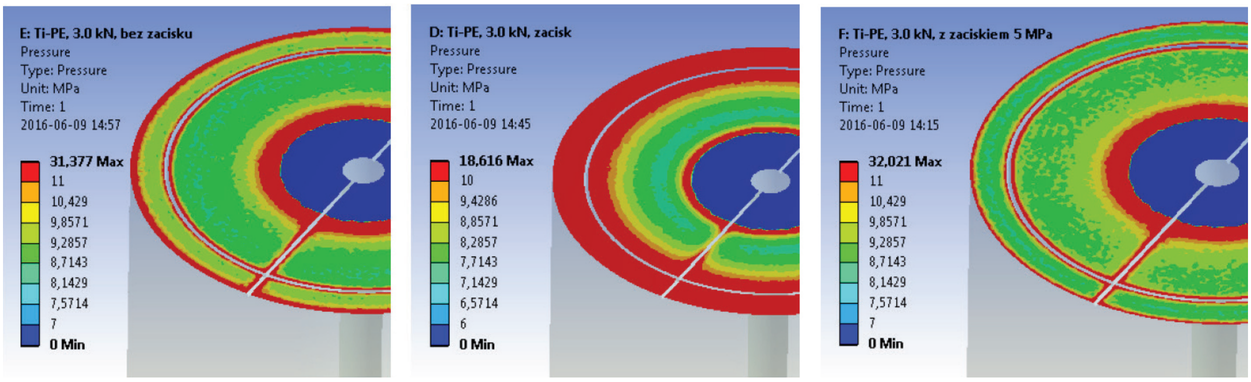

Fig. 3. Contact stress distribution on the polymer specimen's face at 3 kN normal load and three different support conditions (left to right): only back face constrained, back face and cylindrical surface constrained – no radial preload (grip), back face and cylindrical surface constrained – 5MPa radial preload

Rys. 3. Rozkład naprężeń powierzchniowych na czole próbki polimerowej przy obciążeniu 3 kN dla trzech różnych warunków podparcia (od lewej do prawej): tylko tylne czoło utwierdzone, tylne czoło i powierzchnia walcowa utwierdzone – bez zacisku promieniowego, tylne czoło i powierzchnia walcowa utwierdzone – zacisk promieniowy 5 MPa

grip applied to the cylindrical surface. A combination of cone and a threaded connection is used to exert the gripping load on the outer surface of the specimen. The young modulus of PE-UHMW is in the range of 0.7 GPa, while the Ti-13Nb-13Zr can possess the modulus in the range between 41 and 83 GPa, depending on heat treatment of the final product. Because of the difference between the modulus in the two materials ranging over two orders of magnitude any strain in the metallic specimen can be treated as irrelevant as compared to the polymeric one. The model used in the simulation was generated with the use of Ansys FEM environment. The geometry of the specimens was generated accordingly to the original design and the two volumes were arranged as in the actual friction contact. The top (metallic) specimen was constrained at the flat face contacting with the bottom of the chuck. The bottom specimen (polymeric) was analysed in 3 different constraint conditions:

1. Full constraint at the flat face contacting with the bottom of the chuck
2. As in case 1 and frictionless support on the cylindrical surface of the specimen – areas in contact with the sides of the chuck without radial pre-tension,
3. As in case 2, but with 5 MPa uniform radial pre-tension applied to the cylindrical part of the specimen in contact with the chuck.

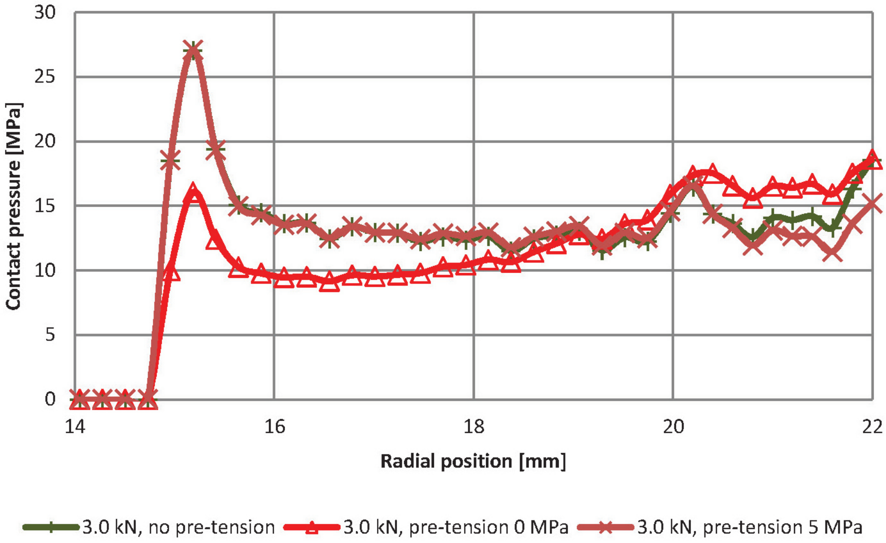

Fig. 4. Simulated surface pressure distribution profile along specimen face radius in three support conditions

Rys. 4. Profil symulowanego rozkładu nacisków wzdłuż promienia czoła roboczego próbki dla trzech wariantów podparcia

The load of 3 kN, as used used during the tests, was applied in simulations to the model of the specimen set. The results shown in **Fig. 3** in the form of surface stress maps revealed clearly visible non-uniformity of the stress. In all 3 cases there was a visible concentration of stress near the centre of the contact face and a minimum of the surface stress at some point along the radius between the inner and outer perimeter of the contact ring. The results shown in **Fig 3** have been transformed into a profile plot shown in **Fig. 4.**

The contact pressure profiles in all 3 cases analysed have a common feature of a certain stress concentration near the ends of the contact zone and a minimum at some point in the middle. Qualitatively the curve is the opposite of the observed wear profile, as shown in

Fig. 2. Further conclusion relevant to both, wear testing and possible applications of the tested material pair, is that the observed wear is clearly dependent of local surface pressure. Also the simulation shows evidence of a possible surface stress control by alteration of the support conditions. Peak pressure is highest at no radial support and at 5 MPa radial pre tension with radial support, but in these two cases, apart from the peak pressure area the load distribution is more equalised than in the case of radial support without pre-stressing. Interestingly, the pressure profile is almost identical in the case of no radial support and 5 MPa pre-stressed radial support.

CONCLUSIONS

The wear rate is contact pressure dependent and uneven intensity of wear along contact face radius can, at least in part, be explained as a consequence uneven surface pressure distribution caused by specimen shape and support. Among other factors influencing the wear observed in the presented research such examples as heat generation, wear debris migration and sliding velocity unevenness can be named, but the comparison of the observed wear and simulation results indicates to the principal role of the analysed factor.

The wear has a characteristics of a running-in process with greater wear depth in stress concentration areas, leading to changes in contact geometry during the test run, load redistribution and, in the end, to contact stress equalisation.

The conditions of the fixation of a cylindrical specimen in the tested system influence the contact pressure distribution in the contact zone.

In the technical terms the wear profile is dependent of the shape of the specimens and the conditions of fixation in the test set up. Both the factors are controllable by either design or procedures used during the preparation of the test. Thanks to the possibility of detailed simulation of the stress distribution it seems possible to equalise the surface stress within the entire contact zone to a level at which the factor will become irrelevant. That observation is also important with regard to the materials' application, because the stress distribution in a useable unit (endoprosthesis) can also be provided with design features helping to equalise the contest stress and decrease wear intensity.

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