**Piotr SIWAK*, Adam PATALAS*, Piotr JABŁOŃSKI*, Katarzyna PETA***

# A TRIBOLOGICAL ASSESSMENT OF UHMW POLYETHYLENE IN DRY AND LUBRICATED CONDITIONS

# OCENA WŁAŚCIWOŚCI TRIBOLOGICZNYCH POLIETYLENU UHMW W WARUNKACH PRACY NA SUCHO I ZE SMAROWANIEM

**Key words:**

tribology, ultrahigh molecular weight polyethylene, UHMWPE, Bruker UMT-2

**Słowa kluczowe:**

tribologia, polietylen wielocząstkowy, UHMWPE Bruker UMT-2

**Abstract**

The aim of the study was to evaluate tribological properties of ultra-high-molecular-weight polyethylene (UHMWPE). This study concerns the areas of both mechanical and biomechanical application fields, including chain guides and knee or hip joint liner replacement. The presented paper describes conducted research on tribological properties of UHMWPE with tribological testing station UMT-2 Bruker. This testing station is capable of conducting

* Poznan University of Technology, Institute of Mechanical Technology, ul. Piotrowo 3, 60-965 Poznań, Poland, e-mails: piotr.siwak@put.poznan.pl, adam.j.patalas@doctorate.put.poznan.pl.

tribological tests of ferrous, non-ferrous metals, plastics, ceramics, composites, and various types of coatings, under both "dry" and liquid and solid lubricating agents. Tests were performed under various conditions, differing in relative speed and the load of interacting frictional pair. Moreover, test duration and the performed number of cycles were considered.

## INTRODUCTION

For decades, tribological studies have allowed the determination of the usefulness of frictional pairs for different applications. This research used a variety of materials, i.e. metals, ceramics, plastics, and composites. Tribological tests included friction, wear, and the lubrication of kinematic pairs. Knowledge about the structures of moving parts is especially important for mechanical engineers, which are moving nodes in friction pairs, such as bearings, guides, gears, clutches, and brakes. Noticeable is a substantial increase in the proportion of plastics in the used materials in the fields of medicine, construction, aviation, and automotive design (Dobrowolska, et al., 2014; Lawrowski, 200; Jasińska, et al., 2013).

In this paper, the research focuses on the ultra-high molecular weight polyethylene, UHMWPE. This material is used in bulletproof vests, guides in the transmission chain, and the joint liner of endoprostheses. These components should be characterized by high reliability and the longest possible service life, so it is important to carry out studies on the time of service life of the materials.

The paper presents research aimed at an assessment of tribological properties of UHMWPE using a test machine UMT-2 Bruker. The device allows the tribological study of ferrous, non-ferrous metals, plastics, ceramics, composites, and various types of coatings in conditions of "dry" and with liquid or solid lubricating agents. UHMWPE has very good biocompatibility, chemical stability, effectively suppresses impact load, and has a low coefficient of friction. Therefore, it has been used as an orthopaedic bearing material of artificial joints over 30 years. Unfortunately, wear products of UHMWPE and the formed particles can induce allergic and inflammatory responses surrounding tissues, which may lead to osteolysis and to aseptic loosening of components. This is recognized as one of the most important factors damaging artificial joints, especially in the case of the prolonged absence of total joint replacement. Currently, much attention is paid to the ingredients of the synovial fluid, such as proteins, hyaluronic acid, etc., which have a significant impact on the process of friction and wear of UHMWPE (Dangsheng & Shirong, 2001) (Wu, et al., 2008) (Sobieraj & Rimnac, 2009) (Ruggiero, et al., 2015) (Guezmil, et al., 2016).

The paper presents the tribological properties of the UHMWPE material. The counter-specimen was a ¾-inch ball of stainless steel. The lubricating agents tested were Ringer's solution, a solution of collagen hydrolysate, and a solution of hyaluronic acid. For comparison, tribological tests were also conducted without lubrication - "dry.”

## METHODOLOGY

The tests were ultra-high molecular weight polyethylene, UHMWPE, under the trade name TIVAR® 1000. TIVAR® 1000 is specified as a polyethylene having a molecular weight of 5 * $10^6$ g / mol manufactured by Quadrant EPP. TIVAR® 1000 is a pressed or extruded material in different colours. In a first step, the samples are prepared in the form of discs 40 mm in diameter and 5 mm in thickness on the turning centre. Due to the lack of the repeatability of the surface structure of samples after treatment in the turning centre, polishing on a mill-grinding machine equipped with a polishing head was carried out. This treatment allowed a reproducible surface structure on all samples. Polishing was done using an aqueous suspension of aluminium oxide with a 0.05 µm particle size.

The research on the tribological properties of UHMWPE was made by working with counter-specimens of austenitic steel ANSI 316L and by using a tribological testing station - Tribotester Bruker UMT-2 in the laboratory at the Faculty of Mechanical Engineering and Management at the Institute of Mechanical Technology of Poznan University of Technology.

a) b)

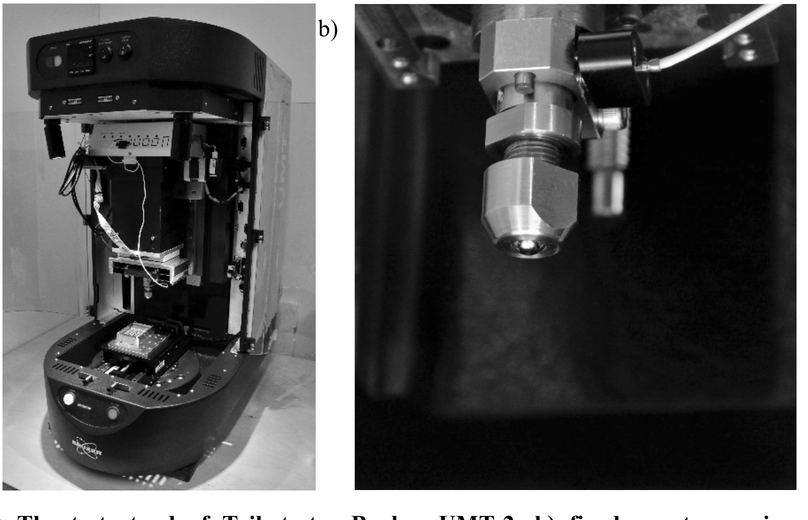

**Fig. 1. a) The test stand of Tribotester Bruker UMT-2, b) fixed counter-specimen of stainless steel 316L**

Rys. 1. a) Stanowisko badawcze typu Tribotester Bruker UMT-2 b) zamocowana przeciwpróbka ze stali 316L

The tribotester is used for tribological testing of ferrous, non-ferrous metals, plastics, ceramics, composites, and various types of coatings, under both "dry" and liquid and solid lubricating agents. Additionally, the tribological testing station is equipped with a heating chamber, which allows the realization of research at a controlled temperature and in inert gas. Tribological tests may be performed by standard methods of evaluation of wear (pin-on-disc or pin-on-flat), which are used for quantitative and qualitative evaluation of engineering materials and biomaterials (Saikko, et al., 2004) (Affatato, et al., 2008) (ASTM G99 - 05, 2010) (ASTM G132 - 96, 2013). The tribological testing station Tribotester Brucker UMT-2 can be programmed for motion in several axes. The trajectory of the sample and counter-sample is a result of motions of the methods of pin-on-disc and pin-on-flat **(Fig. 2)**.

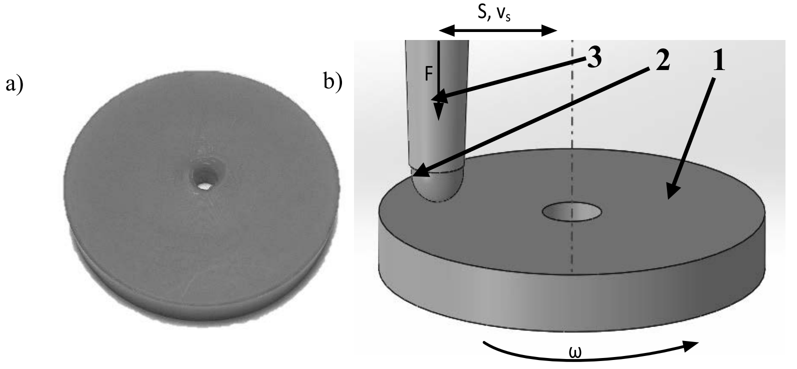


**Fig. 2. a) The prepared sample of UHMWPE, and b) kinematic diagram of the used test method. The elements in the diagram: 1 – a sample of UHMWPE, 2 – counter-sample (ball of steel 316L), 3 – mandrel of counter-sample**

Rys. 2. a) Przygotowana próbka z UHMWPE oraz b) schemat kinematyczny zastosowanej metody badania. Elementy na schemacie 1 – próbka z UHMWPE, 2 – przeciwpróbka (kulka ze stali 316L), 3 – trzpień mocowania przeciwpróbki

The study was conducted using a pin-on-disc method. The sample of UHMWPE makes a rotary motion with the rotational velocity $\omega = 800$ RPM. A counter-sample (stem) performed a reciprocating motion about the direction of the radius of the sample, with an amplitude S = 7.5 mm and a linear velocity $v_s = 1\frac{mm}{s}$ **(Fig. 2)**. The result of two motions – rotating sample and reciprocating counter-sample, resulting in a spiral sliding distance, allows assess the wear over the entire surface of the tests element. During the study, a constant axial load on counter-sample of F = 100 +/-2 N has been applied.

The study was carried out in dry and lubricated conditions. The lubricants agents were applied as a solution of 25% collagen hydrolysate, Ringer's solution, and a 1.5% hyaluronic acid solution. Collagen hydrolysate is a mixture of peptide fragments of different molecular weights, usually coming from animal collagen. Their properties resemble edible gelatine, and it is often used in supplementing foods for physically active people and those with osteoarthritis. Ringer's solution is a crystalloid solution, which is isotonic with the blood of the human. It contains ions of $Na^+$, $K^+$, $Ca^{2+}$, and $Cl^-$. It is used for rehydration, replenishment of electrolytes in the body, and as a solvent for many pharmaceuticals. Hyaluronic acid is a glycosaminoglycan that is present in all living organisms. It is a natural biopolymer that is used in the form of solutions, gels, and as fillers for cavities in the tissue and wrinkles, and they stimulate regeneration processes, e.g., the degenerative changes in the joints. The study used a triple 1.5% hyaluronic acid, which is composed of three types of hyaluronic acid of different molecular weights: 0.5% low molecular weight acid-type SLMW (below 10000 DA), 0.5% low molecular weight acid-type LMW (100 000–400 000 DA), and 0.5% acid type high molecular HMW (1.0–1.8 M DA). The acid solution also contains preservatives (Phenoxyethanol 0.7%, Ethylhexylglycerin 0.05%), and it is in the form of a colourless, transparent gel with a pH of about 6.6. It is a water-soluble substance.

## RESULTS

Each series of measurements was recorded: friction forces, force, friction coefficient, and the value of the acoustic emission. Acoustic emission is defined as the intensity of broadband vibration generated in the solid body when working, wear, and cracking. The intensity of the acoustic emission is used in diagnostic devices for bridges and concrete structures to detect corrosion and formed cracks.

**Figure 3** shows the curves of changes in the coefficient of friction in time for different lubricants during the 1250 minutes (21 hours) **(Fig. 3)**.

The graph indicates that the UHMWPE material cooperating with the counter-sample for the dry conditions are characterized by a coefficient of friction at a constant level in the range of 0.145–0.17. With the application of additional lubricating agents, the coefficient of friction is reduced. The most effective behaviour of these agents is periodic. Average coefficients of friction and the effective operating time of lubricating agents are presented in **Tab. 1**.

The kinetic friction coefficient measurements for lubricating agents, Ringer's solution, and the hyaluronic acid, following the time of effective operation, has been shown to increase the coefficient of kinetic friction. Only measurements for collagen hydrolysate after a time of efficient operation

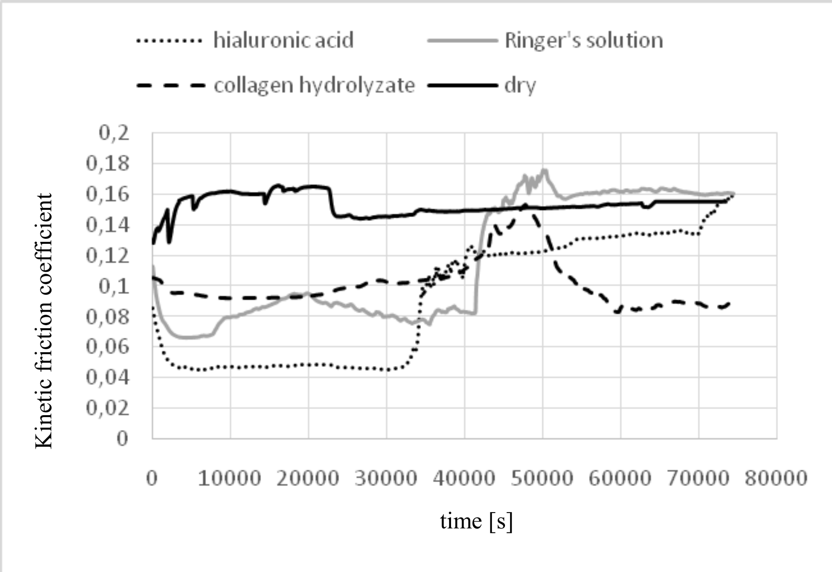


**Fig. 3. Changes in the coefficient of kinetic friction for different lubricating agents**
Rys. 3. Przebiegi zmian współczynnika tarcia kinetycznego dla różnych środków smarujących

**Table 1. The results of tribological tests for various lubricants**
Tabela 1. Wyniki badań tribologicznych dla różnych środków smarujących

| Test | Dry | Hydrolyzed collagen | Ringer's solution | Hyaluronic acid |
|---|---|---|---|---|
| **The mean coefficient of friction during the effective operating time of the lubricant** | 0.0152 | 0.101 | 0.082 | 0.048 |
| **The mean coefficient of friction after the effective operating time of the lubricant** | - | - | 0.153 | 0.0129 |
| **The effective operating time of the lubricant [s]** | - | 41000 | 41500 | 33000 |
| **Amount of cycles performed during the effective operating time of the lubricant** | - | $5.47*10^5$ | $5.53*10^5$ | $4.40*10^5$ |

showed an initial increase in the coefficient of kinetic friction values of 0.15, and they then drop below a value of 0.1 with noticed degradation of collagen hydrolysate. There were fine crystals in the solution, which may be degradation products of the polypeptide chains of collagen, e.g., water insoluble amino acids. Progressive degradation of collagen hydrolysate is shown in the graphs of acoustic emission **Fig. 4**.

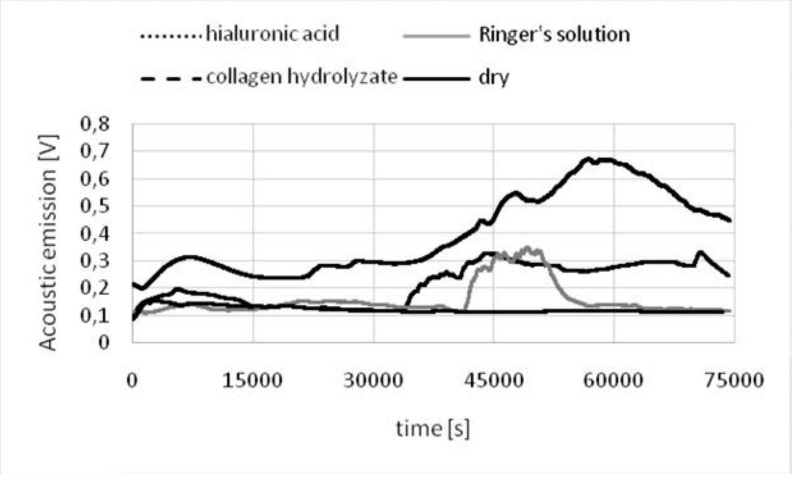


**Fig. 4. Changes of acoustic emission during tribological tests**
Rys. 4. Przebieg zmian emisji akustycznej powstającej w trakcie badań tribologicznych

Additionally, an increase in acoustic emission for hyaluronic acid and Ringer's solution can be seen in **Fig. 4**. An increase in the acoustic emission corresponds to the increase in the coefficient of kinetic friction. It should be noted that the increase in of the acoustic emission testing for tribology UHMWPE in the Ringer solution is temporarily, and for hyaluronic acid, it is a permanent change. This shows progressive degradation of a lubricating agent, which is hyaluronic acid, where the water insoluble fine crystals that are involved in degradation of glycosaminoglycans were also noted.

The surfaces of the UHMWPE samples were measured with a profilometer (Hommel tester T1000). **Table 2** presents the surface roughness of the UHMWPE samples before and after the tribological tests.

**Table 2. Values of surface roughness Ra for the samples before and after the tribological tests: 1) dry, 2) hyaluronic acid, 3) hydrolysed collagen, 4) Ringer's solution**
Tabela 2. Zestawienie wartości chropowatości Ra dla poszczególnych próbek przed i po badaniach tribologicznych; 1) na sucho, 2) kwas hialuronowy, 3) hydrolizat kolagenowy, 4) roztwór Ringera

| Number of sample | Surface roughness Ra before the tribological tests | | Surface roughness Ra after the tribological tests | |
|---|---|---|---|---|
| | average | deviation | average | deviation |
| 1 | 0.084 | +/- 0.034 | 0.58 | +/- 0.353 |
| 2 | 0.082 | +/- 0.018 | 1.545 | +/- 0.358 |
| 3 | 0.078 | +/- 0.025 | 2.404 | +/- 0.871 |
| 4 | 0.072 | +/- 0.016 | 1.116 | +/- 0.155 |

There is a noticeable increase in the roughness, where the highest increases were characterized by testing in the solution of collagen hydrolysate. To include the effects of the lubricating agents on the tribological test, the surfaces were examined for each sample using an atomic force microscope (AFM) a device Quesant Q-Scope 250 **(Fig. 5)**.

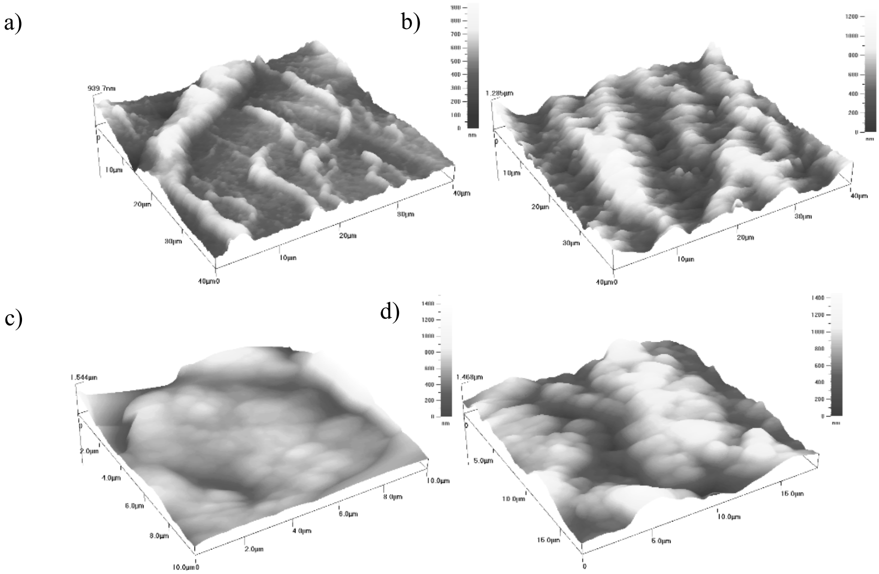

**Fig. 5. Atomic force microscopy (AFM) images of surfaces of samples after tribological tests. Research carried out: a) dry, b) hyaluronic acid, c) hydrolysed collagen, and d) Ringer's solution**

Rys. 5. Powierzchnia próbek po badaniach tribologicznych zobrazowana mikroskopią sił atomowych (AFM). Badania przeprowadzone a) na sucho, b) kwas hialuronowy, c) hydrolizat kolagenowy, d) roztwór Ringera

## SUMMARY AND CONCLUSIONS

The obtained coefficients of friction sliding explicitly depend on the lubricating agents and the time of the cooperation between the UHMWPE material and stainless steel 316L.

Based on the results of research, the evaluation of tribological properties of the UHMWPE material under dry and lubrication condition the following can be stated:

- The tribological testing station UMT-2 Bruker allows for a tribological testing of UHMWPE material and their cooperating with different counter-samples and lubricating agents.
- The lubricating agents and the time of cooperation between sample and counter-sample had an influenced on coefficient of sliding friction. The

smallest coefficient of sliding friction was characterized by the test sample in a solution of hyaluronic acid, obtaining the value of 0.048. It has been noted that, during the tests, the lubricant is degraded. The processes for degradation of collagen hydrolysate and hyaluronic acid solutions were visible.

- The processes of the degradation of the lubricating agents for the solutions of hydrolysed collagen and hyaluronic acid produced visible changes in the values of the acoustic emission.
- The exact mechanism of degradation of these lubricating agents and plastic materials has not been identified, which may be a continuation of the research.
- The continuation of the research should consider the impact of the method of preparing the sample surface (polishing) on the tribochemical properties of the testing material.
- The tribological studies have shown an increased roughness Ra of tested samples. It is one of the effects of surface wear and the reason for the increase in the coefficient of friction, which is in accordance with the demands of molecular-adhesion and the adhesion theory of friction.

## REFERENCES

1. Affatato, S. i inni, 2008. Tribology and total hip joint replacement: Current concepts in mechanical simulation. Medical Engineering & Phisics, pp. 1305–1317.
2. ASTM G132-96 Standard Test Method for Pin Abrasion Testing (2013) Standard Test Method for Pin Abrasion Testing.
3. ASTM G99-05 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. (2010) Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus.
4. Dangsheng, X. i Shirong, G., 2001. Friction and wear properties of UHMWPE/Al2O3 ceramic under different lubricating conditions. Wear, Tom 250, pp. 242–245.
5. Dobrowolska, A., Kowalewski, P. i Ptak, A., 2014. Wpływ nacisku jednostkowego na współczynnik tarcia statycznego wybranych par ślizgowych metal-polimer. Tribologia, Issue 4, pp. 21–32.
6. Guezmil, M., Bensalah, W. i Mezlini, S., 2016. Effect of bio-lubrication on the tribological behavior of UHMWPE against M30NW stainless steel. Tribology International, Issue Volume 94, pp. 550–559.
7. Jasińska , R., Kowalewski, P. i Litwin, A., 2013. Wpływ zużycia zmęczeniowego PEUHMW stosowanego na panewki endoprotez na jego własności tribologiczne. Tribologia, Issue 2, pp. 95–102.
8. Lawrowski, Z., 2008. Tribologia. Tarcie, zużycie i smarowanie. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej.

9. Ruggiero, A., D'Amato, R., Gómez, E. i Merola, M., 2015. Experimental comparison on tribological pairs UHMWPE/TIAL6V4 alloy, UHMWPE/AISI316L austenitic stainless and UHMWPE/AL2O3 ceramic, underdry and lubricatedconditions. Tribology International, Issue 96, pp. 349–360.
10. Saikko, V., Calonius, O. i Keränen, J., 2004. Effect of slide track shape on the wear of ultra-high molecular weight polyethylene in a pin-on-disk wear simulation of total hip prosthesis.. Journal of Biomedical Materials Research Part B: Applied Biomaterials., Issue 69, p. 141–148.
11. Sobieraj, M. C. i Rimnac, C. M., 2009. Ultra high molecular weight polyethylene: Mechanics, morphology, and clinical behavior (Review). Journal of the Mechanical Behavior of Biomedical Materials, 2(5), pp. 433–443.
12. Wu, G., Zhao, C. H. i Zhao, X. Z., 2008. Progress and prospect of friction and wear properties of ultra high molecular weight polyethylene (Review). Journal of Clinical Rehabilitative Tissue Engineering Research, 45(12), pp. 8893–8896.

**Streszczenie**

**Celem pracy jest ocena właściwości tribologicznych polietylenu wielocząstkowego w odniesieniu do aplikacji mechanicznych oraz biomedycznych, m.in. prowadnic w przekładniach łańcuchowych oraz elementów pośrednich (przekładek) endoprotez stawowych. W pracy przedstawiono badania mające na celu kompleksową ocenę właściwości tribologicznych UHMWPE za pomocą wielopróbkowego stanowiska badawczego UMT-2 Bruker. Urządzenie pozwala na badania tribologiczne materiałów żelaznych, nieżelaznych, tworzyw sztucznych, ceramiki, kompozytów, jak i różnego rodzaju powłok w warunkach „na sucho" oraz smarowania środkami ciekłymi i stałymi. Badania tribologiczne prowadzono w różnych warunkach, tj. przy zadanej prędkości względnej współpracującej pary ciernej, siły obciążająca parę trącą, temperatury, określonej częstotliwości, ilość przeprowadzanych cykli pracy oraz przerwy między nimi z zastosowaniem różnych środków smarujących.**