

Rafał KOZDRACH*

THE INFLUENCE OF DIFFERENT VEGETABLE DISPERSION PHASES ON THE ROLLING CONTACT FATIGUE OF BIODEGRADABLE LUBRICATING GREASES

WPLYW ROŚLINNEJ FAZY DYSPERGUJĄCEJ NA POWIERZCHNIOWĄ TRWAŁOŚĆ ZMĘCZENIOWĄ BIODEGRADOWALNYCH SMARÓW PLASTYCZNYCH

Key words:

vegetable oils, biodegradable lubricating grease, rolling contact fatigue, four-ball machine, pitting, Weibull curve

Słowa kluczowe:

oleje roślinne, biodegradowalny smar plastyczny, powierzchniowa trwałość zmęczeniowa, aparat czterokulowy, pitting, krzywa Weibulla

Abstract

The paper discusses the influence of the vegetable dispersion phase on the rolling contact fatigue of bearings lubricated with ecological lubricating compositions. Four vegetable oils were used for the production of lubricating greases: rapeseed, sunflower, soybean, and castor. For comparison purposes,

* The Institute of Sustainable Technologies – NRI, Radom, ul. Pułaskiego 6/10, Poland, tel. (048) 36-442-41, fax (048)63-447-65, e-mail: rafal.kozdrach@itee.radom.pl.

the synthetic and mineral oils were used as well. The rolling contact fatigue (pitting) of bearings lubricated with particular compositions were investigated and evaluated for each base oil. The tribological tests were carried out using T-03 four-ball machine under high load conditions.

Based on the obtained results, it may be concluded that vegetable oils, such as rapeseed, sunflower and castor, as the base of lubricating grease positively affected the rolling contact fatigue of tribosystems lubricated with the above-mentioned compositions in comparison to the control lubricated with greases based on mineral or synthetic oil. There is no favourable change in rolling contact fatigue of tribosystems lubricated with greases based on soybean oil.

INTRODUCTION

Nowadays, the constantly growing attention on environmental protection is observed. EU legislation and policy puts emphasis on a reduction in the use of environmentally harmful petroleum lubricants [L. 1–3]. As the alternative for the paraffin base oils, the readily biodegradable and non-toxic vegetable bases are frequently mentioned [L. 4–7]. The lubricating compositions for food industry should demonstrate the ecological character understood as containing as little toxic chemicals as possible. The production of lubricants revealing suitable properties requires the use of base oils that guarantee no danger for the natural environment [L. 8–15].

At present, there is a strong demand for lubricating greases based on vegetable oils, combining good lubricating properties with their harmlessness to the environment. There is a tendency to replace petroleum-based lubricants with non-toxic readily biodegradable vegetable counterparts [L. 16–18]. The vegetable oils have a very good viscosity-temperature as well as lubricating properties, which determine their suitability as a base for lubricating greases. The major disadvantages of these products are low resistance to hydrolysis, low thermal stability, and susceptibility to oxidation [L. 19–23].

The one of the most frequent forms of wear, which deteriorates the working elements of machines and devices, is surface fatigue wear called pitting. This type of wear is caused by the cyclic stresses in the areas where the material is in contact with the lubricant. The cause of pitting is the fatigue of the surface layer. The process of spall wear consists of three phases: the early formation of cracks due to fatigue, the extension of the cracks due to the injection of the lubricating grease, and finally the pulling out of the particles of material from the surface layer. The surface fatigue wear depends on many factors, e.g., the properties of the material, the conditions of working, the construction of the tribosystem, and physicochemical properties of the lubricating compositions. [L. 4–10]. This form of wear is characteristic for

rolling friction with the side, as well as for dry friction and leads to the loss of properties of the lubricated elements.

The aim of this work was the analysis of various types of vegetable oils as a base for lubricating compositions and their influence on the surface fatigue wear of bearings in food industry.

THE SUBJECT AND METHODOLOGY OF RESEARCH

A group of model lubricating compositions made of non-toxic components were prepared. As the dispersion phase, the author used the vegetable base oils of the best tribological and physicochemical properties. The base oils used for the preparation of greases were refined prior to the processing. For comparison, paraffin and polyalphaolefin oils (PAO-8) were used as a control [L. 19–20, 22, 24–26]. In the role of dispersed phase, the amorphous silica Aerosil (particle size 7–40 nm) was used. The lubricating compositions were prepared to comply with the second class of consistency for the use in the food industry. The consistencies of prepared compositions were investigated according to the requirements of ISO 2137:2011, using a laser penetrometer developed by ITeE – PIB.

The lubricating compositions were marked as follows: Grease A – based on rapeseed oil, Grease B – based on sunflower oil, Grease C – based on castor oil, and Grease D - based on soybean oil. As a control, Greases E and F were based on mineral (paraffin) and synthetic (polyalphaolefin) oils, respectively. The prepared lubricating compositions were tested for their tribological properties.

The tribological properties of the lubricating compositions were evaluated according to a standardized procedure described in IP 300/82 on a modified four-ball machine T-03. The evaluation procedure was based on the estimation of the surface fatigue wear of the rolling tribosystem during 24 runs under a constant load of 5886 N and a constant speed of 1450 rpm. The actual test elements were the ½" bearing balls made of 100Cr6 steel, which had a surface roughness of 0.032 mm and a hardness of about 60-65 HRC. The test set-up was constantly measured for vibrations, and the test was automatically intermitted when the permissible level of vibrations reached the defined limit. The run was accepted when crumbling appeared on the top ball. If chipping occurred on one of the lower balls, the run was rejected. The result of each run is defined by the time in minutes. The results of individual runs were ranked from the shortest to the longest. Each result received the percentage value of the probability of the ball damage. According to the IP 300-82 standard method, the time vs. probability of damage were marked on the Weibull graph. Such prepared graphs provided the values of L_{10} and L_{50} , defining the durability of the tribosystem at 10% and 50% probability of damage, respectively [L. 12,

27–32]. Based on pitting time values, the accumulated percentage of damages was calculated as follows:

$$\text{The probability of damage} = i/(n+1)*100 [\%],$$

where: I – the run number, and

n – the number of runs terminated with pitting (n = 24).

The viscosity-temperature characteristics of oils used as a base for the tested lubricating compositions are shown in **Table 1**. Their chemical composition is listed in **Table 2**.

Table 1. The viscosity-temperature characteristics of oils used as a base of lubricating compositions

Tabela 1. Charakterystyki lepkościowo-temperaturowe olejów bazowych użytych do wytworzenia kompozycji smarowych

The parameter to be tested	The test method	The unit	The base oils					
			soybean	rape-seed	castor	sunflower	PAO 8	paraffine
The kinematic viscosity in 40°C	PN-EN ISO 3104:2004	mm ² /s	31.87	36.24	266.4	32.44	46.84	73.67
The kinematic viscosity in 100°C	PN-EN ISO 3104:2004	mm ² /s	7.522	7.754	14.93	7.657	7.963	8.762
The viscosity index	PN-ISO 2909:2009	-	217	192	19	218	141	89
The pour point	PN-ISO 3016:2005	°C	-18	-20	-32	-11	-62	-14

Table 2. The chemical composition of vegetable oils used as a base for lubricating compositions [L. 33]

Tabela 2. Skład chemiczny roślinnych olejów bazowych użytych do wytworzenia kompozycji smarowych [L. 33]

The tested oil	The content of saturated fatty acids [%]	The content of monounsaturated fatty acids [%]	The content of polyunsaturated fatty acids [%]
rapeseed	7.4	63.3	28.1
sunflower	10.3	19.5	65.7
castor	12.9	27.6	54.7
soybean	15.7	22.8	57.7

RESULTS AND DISCUSSION

Figures 1a–f presents the Weibull graphs obtained for the lubricating compositions based on vegetable as well as based on synthetic and mineral base oils. The formulas and the R² correlation coefficients are included.

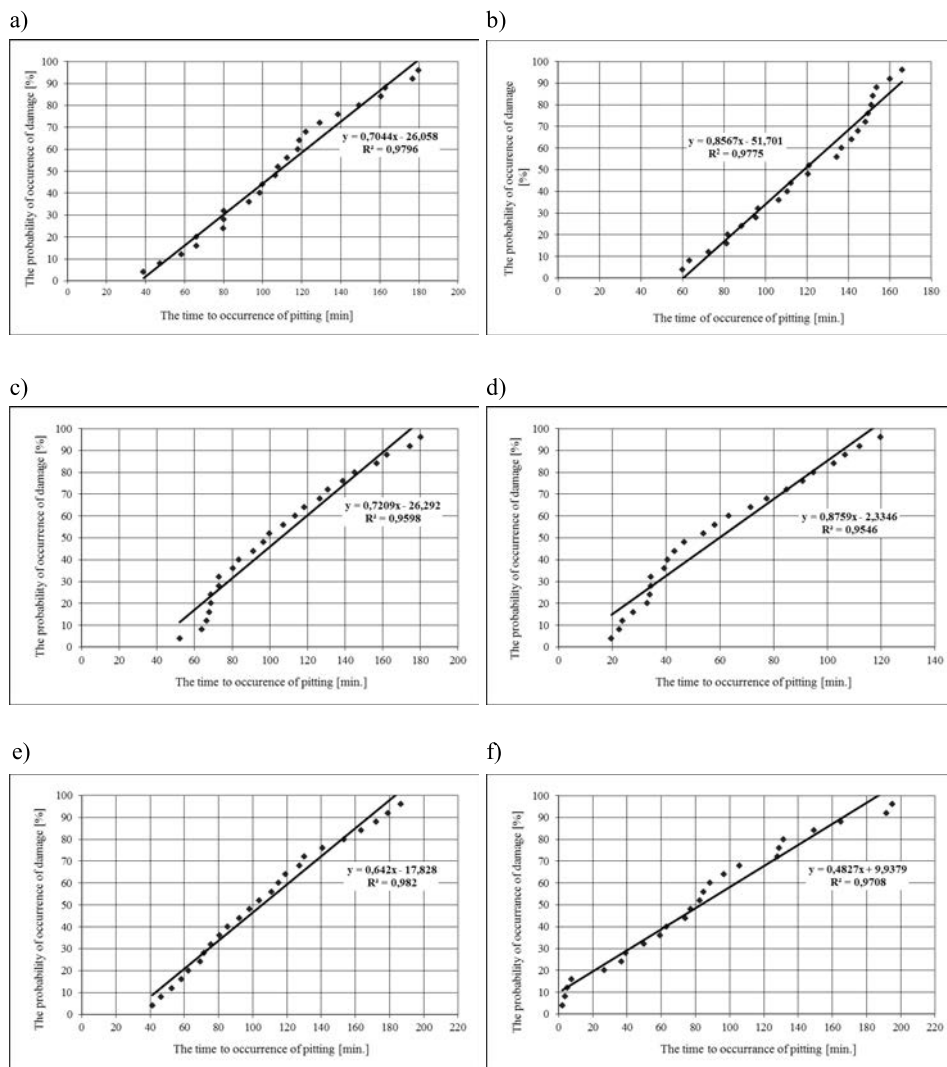


Fig. 1. The probability of damage of the upper ball of the tribosystem lubricated with greases based on: a) rapeseed oil, b) sunflower oil, c) castor oil, d) soybean oil, e) mineral (paraffin) oil, f) synthetic (polyalphaolefin) vs. time of pitting

Rys. 1. Zależność prawdopodobieństwa wystąpienia uszkodzenia na kulce górnej dla wężła tarcia smarowanego smarem plastycznym wytworzonym na oleju: a) rzepakowym, b) słonecznikowym, c) rycynowym, d) sojowym, e) mineralnym (parafinowym), f) syntetycznym (polialfaolefinowym) od czasu wystąpienia pittingu

Based on obtained results, the author calculated the time after which 10% and 50% of the tested tribosystems were damaged – L_{10} and L_{50} , respectively. These results are shown in **Figs. 2–3**.

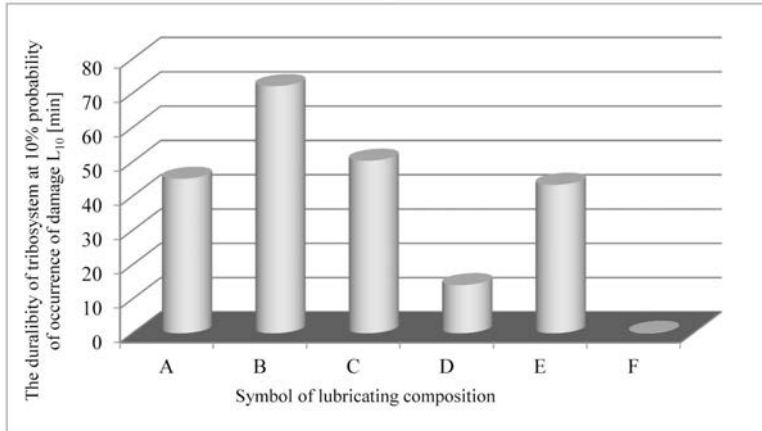


Fig. 2. The comparison of durability of particular tribosystems at 10% probability of damage – L_{10}

Rys. 2. Porównanie trwałości węzła tarcia przy 10% prawdopodobieństwie wystąpienia uszkodzenia łożyska dla badanych smarów plastycznych – L_{10}

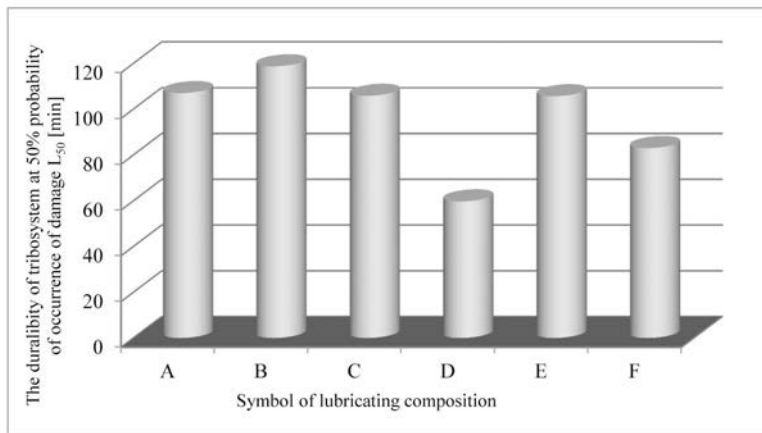


Fig. 3. The comparison of durability of particular tribosystems at 50% probability of damage – L_{50}

Rys. 3. Porównanie trwałości węzła tarcia przy 50% prawdopodobieństwie wystąpienia uszkodzenia łożyska dla badanych smarów plastycznych – L_{50}

The analysis of data presented in **Figs. 2 and 3** indicate that the rolling contact fatigue of the tribosystem depends on the oil base of the lubricating composition. The compositions based on rapeseed oil revealed the L_{10} and L_{50} values at 45.08 min and 107.00 min, respectively. In the composition where sunflower oil was used as the dispersion phase, the durability of the tribosystem was 72.08 min for L_{10} and 118.71 min for L_{50} . Castor oil as the base resulted in L_{10} at 50.34 min and L_{50} at 105.83 min. Finally, the composition based on soybean oil L_{10} was 14.08 min and L_{50} was 59.75 min.

To compare the obtained results with petroleum counterparts, additional test runs were performed for the tribosystems lubricated with compositions based on mineral (paraffin) and synthetic (polyalphaolefin) oils. In this case, the durability of tribosystem represented by L_{10} was 43.34 min and 0.13 min respectively. The values of L_{50} were 105.65 min and 82.99 min, respectively.

One of the crucial factors causing pitting is the kinematic viscosity of the lubricant (oil). The increase in viscosity delays pitting that leads to smaller defects formed on the surface. Sometimes it happens that the lubricant of suitable viscosity efficiently protects from pitting.

Based on physicochemical properties of vegetable base oils, it was assumed that their differentiation certainly affects their efficiency against pitting, which was actually observed during the tests. Such diversity in the physicochemical properties of vegetable dispersion phases is caused by their different chemical structure and is the consequence of different intermolecular interactions, especially van der Waals forces. This assumption proves the strict dependency between the intermolecular forces and the tribological properties such as protection against pitting.

The tests performed on the mentioned lubricants did not lead to a simple correlation between the kinematic viscosity or pour point of the oil base and the L_{10} and L_{50} values that is the stability of tribosystem at 10% and 50% the probability of damage. However, the physicochemical parameters of base oils have an essential influence on the evaluation of the effectiveness against rolling contact fatigue (pitting).

The several hundred-fold increase in stability of the tribosystem defined by L_{10} was observed for lubricating compositions based on rapeseed, castor, sunflower, and soybean base oils when compared to the synthetic oil. The increase of tribosystem durability was about 66.31% for sunflower oil, about 16.15% for castor oil and about 4.01% for rapeseed oil as the dispersion phase of lubricating greases used in the experiments. In contrast, the lubricants based on soybean oil caused a decrease in tribosystem durability of about 67.5% in comparison to the control, where a mineral oil was applied.

The use of rapeseed, sunflower, or castor oil as a base oil increases the tribosystem durability in relation to the compositions prepared on mineral or synthetic oils. The analysis of graphs indicated that the rolling contact fatigue of tribosystem at 50% of the probability of damage increased by about 28.9%, 43%, and 27.5% for rapeseed, sunflower, and castor base oil, respectively, when compared to the synthetic base oil. In contrast, the use of soybean oil as a base showed a significant decrease in tribosystem durability of about 28% when compared to synthetic oils. In comparison to the control lubricated with mineral-based greases, there was also an increase in rolling contact fatigue of tribosystem of about 12.36%, for sunflower oil, about 1.28% for rapeseed oil and about 0.17% for castor oil. The lubricating composition based on soybean

oil caused a decrease in tribosystem durability of about 43.44% in comparison to the composition composed of the mineral base oil.

The use of vegetable oils as a dispersion phase of lubricating greases, in most cases (without a composition based on a soybean oil), indicated a positive impact on susceptibility to rolling contact fatigue. The significant improvement of tribosystem durability at 50% of the probability of damage (L_{50}) of more than 20% was observed. This remark refers to the controls where both mineral and synthetic base oil were applied. However, the tribosystem durability at 10% of the probability of damage (L_{10}) for most vegetable-based compositions (except soybean oil) revealed higher values of this parameter when compared to the composition based on mineral base oil. It should be admitted that the L_{10} values for all lubricating compositions were several hundred-fold higher than for the compositions based on synthetic base oil.

SUMMARY

Based on obtained results, it may be assumed that the use of rapeseed, sunflower, or castor oils as a dispersion phase of lubricating greases has a positive effect on changes in the rolling contact fatigue of the tested lubricating compositions. No favourable changes of rolling contact fatigue for the lubricating composition based on soybean were observed. The change of the fatigue durability of tested greases depends on the chemical structure and physicochemical properties of base oils used as their bases. The fatigue durability of tribosystems characterized by the of L_{10} and L_{50} parameter indicated that the vegetable-based lubricating compositions, in most cases (except from soybean oil), revealed much higher resistance on the rolling contact fatigue than the compositions based on mineral or synthetic oil.

The effectiveness against pitting is strongly dependent on the chemical structure and physicochemical characteristics of particular vegetable base oil, and it is caused by various intermolecular interactions like van der Waals forces.

The type of base oil used to form the particular lubricating composition, and partially its viscosity and pour point, significantly affects the susceptibility to rolling contact fatigue. However, the clear relationship between the viscosity or pour point of the dispersion phase and the fatigue durability of tested lubricating compositions was not observed. Notwithstanding, the physicochemical parameters of base oils have a fundamental meaning for the estimation of the effectiveness against pitting.

The poor resistance to rolling contact fatigue of lubricating composition based on soybean oil may result from a higher content of saturated fatty acids than in other oils used in the experiment.

The decrease in fatigue durability of compositions based on polyalphaolefin oil, which typically creates very durable lubricating layers, might be caused by tribochemical by-products rising within the tribosystem.

More accurate explanation of such effectiveness of vegetable base oils in comparison to 'classic' petroleum counterparts requires more research on the surface layer and changes that occurred after the tribological tests. It may be done using X-ray photoelectron spectrometer (XPS). Additional research should also include different grease thickeners, such as lithium 12-hydroxystearate or calcium stearate.

REFERENCES

1. Mosleh M., Bradshaw K.: Role of component configuration in evaluation of accelerated rolling contact fatigue of ball bearings, *Wear* 271(2011), s. 2681–2686.
2. Biresaw G., Ahhvaryu A., Erhan S.Z.: Friction properties of vegetable oils, *Journal of the American Oil Chemists Society*, 7/2003, pp. 697–704.
3. Fox N.J., Stachowiak G.W.: Vegetable oil-based lubricants-A review of oxidation, *Tribology International*, 7/2007, pp. 1035–1046.
4. Hebda M., Wachal A., *Tribology*, WNT, Warszawa 1980 (in Polish).
5. Lawrowski Z., *Tribology. Friction, wear and lubrication*, PWN, Warszawa 1993 (in Polish).
6. Pytko S., Szczerek M., Pitting – the form of destruction of rolling elements, *Tribology*, 4/5 1993, pp. 317–333 (in Polish).
7. Pawelec E., Drabik J.: The possibility of application of non-toxic oils for lubricating the rolling and sliding bearings – *Tribology* 5/2006, pp. 57–66 (in Polish).
8. Szczerek M., *The methodology problems of systematization experimental tribological tests*, wyd. ITeE, Radom 1996 (in Polish).
9. Krzemiński-Freda H., *The rolling bearings*, PWN, Warsaw 1989 (in Polish).
10. Waligóra W., *The surface layer of elements from bearing steel, and its resistance on surface fatigue*, *Tribology*, 2/1993, pp. 199–219 (in Polish).
11. Kozdrach R.: The influence of mechanical forces for change of lubricating properties of biodegradable lubricating grease made on vegetable base, *Nafta-Gaz* 11/2012, pp. 868–876 (in Polish).
12. Kozdrach R., Molenda J.: The testing of exploitation properties of ecological greases modified with polimer-silica additive, *Tribology* 6/2012, pp. 99–111 (in Polish).
13. Rogoś E.: Study on vegetable oils as bases of technical oils. *Przemysł Chemiczny*, 2016, (95) nr 1, pp. 103–106 (in Polish).
14. Grądkowski M., Rogoś E., Urbański A.: Lubricity of selected vegetable oils – *Tribology* 3/2001, pp. 381–393 (in Polish).
15. Rogoś E.: Lubricating properties of modified rape oil – *Tribology* 2/2005, pp. 99–108 (in Polish).
16. Drabik J., Pawelec E., Janecki J.: Characteristic of the biodegradable base oils of ecological greases– *Tribology* 5/2003, pp. 23–37 (in Polish).

17. Drabik J., Hłowska J., Gniady J., Kozupa M., Szmatoła M, Semeniuk I.: Effect of the base oil and thickener composition on the performance characteristics of greases – *Przemysł Chemiczny* 10/2012, pp. 1922–1926 (in Polish).
18. Tuszyński W., Szczerek M., Michalczewski R., Osuch-Słomka E., Rogoś E., Urbański A.: The potential of the application of biodegradable and nontoxic base oils for the formulation of gear oils – model and component scuffing tests. *Lubrication Science* Volume:26 Issue: 5 Special Issue: SI Pages: 327–346. Published: August 2014.
19. Arnsek A., Visintin J., Pitting resistance of rapeseed based oils, *Journal of the Society of Tribologists and Lubrication Engineering*, 3/2001, pp. 926–938.
20. Piekoszewski W., Szczerek M., An influence of lubricants on the base of vegetable oils on surface fatigue life, *Tribology*, 1/2007, pp. 127–135 (in Polish).
21. Paredes X., Comunas M.J.P., Pensado A.S., Bazile J.P., Boned Ch. et. al.: High pressure viscosity characterization of four vegetable and mineral oils, *Industrial Crops&Products*, 54/2014, pp. 281–290.
22. Piekoszewski W., Tuszyński W., Rolling contact fatigue life for elements lubricated with mineral and synthetic base oils, *Tribology*, 3/2004, pp. 351–361 (in Polish).
23. Hłowska J., Bereska B., Drabik J., Kozdrach R.: The oxidation stability and lubricating properties of oil compositions, *Tribology* 5/2011, pp. 69–80 (in Polish).
24. Buczyński P., The synthetic lubricants for industry, *The Fuels, Oils and Greases in Exploitation*, 5/1993, pp. 5–7 (in Polish).
25. Wang Y., Fernandez J.E., Cuervo D.G., Rolling contact fatigue lives of steel AISI 52100 balls with eight mineral and synthetic lubricants, *Wear*, 196/1996, pp. 111–119.
26. Kozdrach R.: The influence of a type of dispersion phase on the tribological properties of lubricating greases, *Tribology* 6/2012, pp. 85–97 (in Polish).
27. Pawelec E., Drabik J., Janecki J., Fatigue live of bearing lubricated with non-toxic grease, *Tribology*, 2/2002, pp. 555–561 (in Polish).
28. Pawelec E., Drabik J.: The change of fatigue life of rolling bearings as effect of an interaction between grease components and friction elements surface – *Tribology* 1/2007, pp. 115–125 (in Polish).
29. Rico J.E., Battez A., Cuervo D.G., Rolling contact fatigue in lubricated contacts, *Tribology International*, 36/2003, pp. 35–40.
30. Piekoszewski W., Szczerek M., Tuszyński W., The modification of four-balls tribological tests, *Tribology* 5, 6/1997, pp. 818–825 (in Polish).
31. Michalczewski R., Piekoszewski W., Wulczyński J., The method for investigation of rolling contact fatigue of coated elements, *Maintenance Problems*, 4/2003, pp. 91–99 (in Polish).
32. Łubiński J., Śliwiński P.: Multi parameter sliding test result evaluation for the selection of material pair for wear resistant components of a hydraulic motor dedicated for use with environmentally friendly working fluids, *Solid State Phenomena*, nr 225(2015), pp. 115–122.
33. Beran E., Effect of chemical structure on biodegradability and some service properties of lubricating base oils, *Oficyna Wydawnicza Politechniki Wrocławskiej*, Wrocław, 2008 (in Polish).

Streszczenie

W publikacji przedstawiono wyniki badań dotyczących wpływu roślinnej fazy dyspergującej na wartość trwałości zmęczeniowej łożysk smarowanych ekologicznymi kompozycjami smarowymi. Ocenie poddano kompozycje wytworzone na następujących olejach roślinnych: rzepakowym, słonecznikowym, rycynowym i sojowym, a także dla porównania na oleju syntetycznym i mineralnym. Wykonano badania powierzchniowej trwałości zmęczeniowej (pitting) łożysk smarowanych kompozycjami sporządzonymi na wyżej wymienionych olejach. Następnie oceniono wpływ poszczególnych olejów bazowych na zmiany powierzchniowego zużycia zmęczeniowego łożysk. Badania przeprowadzono na aparacie czterokulowym – typ T-03. Na podstawie analizy uzyskanych wyników stwierdzono, że zastosowanie olejów roślinnych takich jak: rzepakowy, słonecznikowy i rycynowy jako bazy olejowej wytworzonych kompozycji smarowych wpływa korzystnie na zmiany powierzchniowej trwałości zmęczeniowej węzłów tarcia smarowanych wyżej wymienionymi kompozycjami w porównaniu z kompozycjami smarowymi, gdzie jako fazę dyspergującą zastosowano olej mineralny bądź syntetyczny. Nie zaobserwowano tak korzystnych zmian powierzchniowej trwałości zmęczeniowej w przypadku kompozycji wytworzonej na bazie oleju sojowego.

