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ECOLOGY IN TRIBOLOGY: SELECTED PROBLEMS OF ELIMINATING NATURAL OIL-BASED LUBRICANTS FROM MACHINE FRICTION COUPLES

EKOLOGIA W TRIBOLOGII: WYBRANE PROBLEMY ZWIĄZANE Z ELIMINACJĄ ROPOPOCHODNYCH ŚRODKÓW SMAROWYCH W WĘZŁACH CIERNYCH

Key words: ecology, polymer bearing materials, water-lubricated bearings, material properties.

Abstract: The elimination of mineral oil-based lubricants from machines has multiple beneficial effects on the natural environment. Firstly – these lubricants are a direct threat to the environment in the event of leaks; secondly – their elimination reduces the demand for crude oil from which they are obtained. In addition, in many cases, e.g. when replacing traditional lubricants with water, friction losses in the bearings can also be reduced due to the lower viscosity of the water, which reduces the energy dissipation in machines.

On the other hand, the introduction of self-lubricating materials or water-lubricated bearings causes problems related to the need to adapt the design of machines and materials used to new operating conditions and changed properties of the lubricants. In the paper, selected examples of problems related to the use of ecological lubricants are discussed. The high cost of PEEK based polymers resulted in the emergence of cheaper substitutes on the market; however, in the conducted research, the substitutes presented worse properties than those declared by their manufacturers.

Słowa kluczowe: ekologia, polimerowe materiały ślizgowe, łożyska smarowane wodą, właściwości materiałowe.

Streszczenie: Eliminacja ropopochodnych środków smarowych z węzłów ciernych maszyn ma wieloraki korzystny wpływ na stan środowiska naturalnego. Po pierwsze – środki te są bezpośrednim zagrożeniem dla środowiska w przypadku wycieków i nieszczelności, po drugie – ich eliminacja zmniejsza zapotrzebowanie na ropę naftową, z której są pozyskiwane. Ponadto w wielu wypadkach, np. przy zastępowaniu tradycyjnych środków smarowych wodą, zmniejszają się też straty tarcia w łożyskach w wyniku mniejszej lepkości wody, co zmniejsza straty energii w maszynach. Z drugiej jednak strony wprowadzanie bezsmarowych węzłów ciernych lub smarowania wodnego w łożyskach przysparza problemów związanych z koniecznością dostosowania konstrukcji maszyn i stosowanych materiałów do nowych warunków działania łożysk i innych właściwości środków smarowych. W pracy omówiono kilka przykładowych problemów związanych ze stosowaniem ekologicznych środków smarowych. Jednym z nich jest dobór polimerowych materiałów stosowanych na łożyska smarowane wodą. W związku z wysokimi kosztami materiałów na bazie PEEK na rynku pojawiają się tańsze zamienniki. W przeprowadzonych badaniach materiałowych zaobserwowano niezgodność deklarowanych przez producentów właściwości z rzeczywistością. Stwierdzono również wyraźnie gorsze właściwości tribologiczne.

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INTRODUCTION

The importance of environmental protection has been discussed for many decades, but due to the observed climate changes and scientific analyses, have recently become one of the most important global issues.

Tribology research can also have an impact on the environment, which has been documented for the first time in the 1960s by the well-known Jost report **[L. 1]**, where the losses and costs generated by friction and wear of the machine elements were evaluated by the team led by P. Jost. The report provided an analysis of the potential financial benefits of investing in tribological research and recommendations for pursuing such an endeavour. Holmberg and Erdemir **[L. 2]** published a similar report based on contemporary data. In a very thorough and well-documented study, they describe potential benefits in energy saving and emission reduction that can be achieved thanks to the new developments in tribology. Their study starts with an estimate of the global energy consumption, cost, and emissions, due to friction and wear, estimated separately (**Fig. 1**)

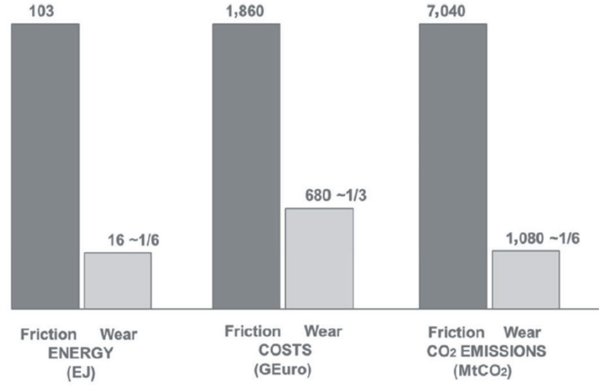

Fig. 1. Global energy consumption, costs, and CO_2 emissions due to wear and friction [L. 2]
Rys. 1. Światowe zużycie energii, ponoszone koszty i wielkość emisji CO_2 wynikające z tarcia i zużycia **[L. 2]**

Further to that cost assessment, a perspective of savings is presented by Holmberg and Erdemir, thanks to the application of the results of scientific research. These potential savings in the selected areas are graphically shown in **Fig. 2**.

In this paper, only a selected example of the broad spectrum of the developments proposed generally in **[L. 2]** is discussed, namely conversion from mineral oil lubrication to water lubrication in a journal sliding bearing. There are two potential benefits – one, lower friction losses due to the lower viscosity of the lubricant, and the other, a decrease in the volume of the lubricants produced from crude oil, which is an obvious result of switching to water lubrication. Approximately 1% of total crude oil production is used to produce lubricants, i.e. 37 million tons in 2020 **[L. 3]**, in comparison to approximately 4,000 million tonnes of crude oil production in 2020 **[L. 4]**.

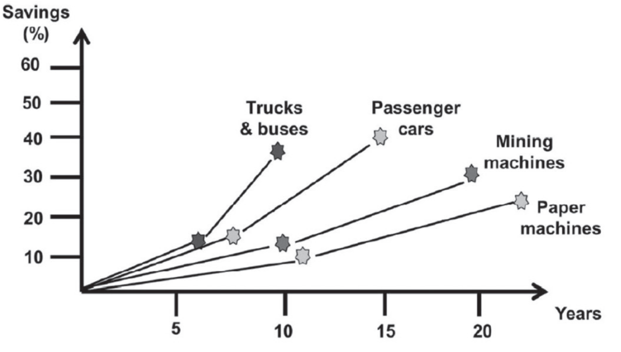

Fig. 2. Perspective of energy consumption saving in selected groups of machinery [L. 2]
Rys. 2. Perspektywy zmniejszenia zużycia energii przez różne rodzaje maszyn **[L. 2]**

EXAMPLE OF AN APPLICATION GOAL

The discussed example would be the introduction of a water-lubricated bearing as an environmentally friendly retrofit to a machine originally equipped with oil-lubricated bearings. In such a case, in order not to change the design of the machine, the space occupied by the bearing and its housing should not change too much; also, the rotational speed should remain the same. It means that the sliding speed and the specific load should be of the same order as in an oil-lubricated bearing. The bearing data and its operating conditions are presented in **Table 1**. More details on the tests are presented in **[L. 5]**.

Table 1. Test bearing and test conditions
Tabela 1. Dane łożyska badawczego i warunki badań

Parameter	Value
Bearing diameter	95 mm
Bearing axial length	80 mm
Circumferential length	160°
Bearing bush material	Modified PEEK
Rotational speed/sliding speed	600 rpm/2.98 m/s
Radial load/specific load	18 kN/2.4 MPa
Lubrication	ISO VG 46 oil/ pure water

In the research, which was carried out with the use of a PEEK-lined journal bearing, among others, the tests were carried out aimed at finding parameters of the transition to mixed friction for a bearing lubricated with oil or water. The results are shown in **Fig. 3**. According to the theory, the minimum friction coefficient is observed at the transition point from fluid to mixed friction. In the tested bearing, one can see that the minimum was not observed in an oil-lubricated bearing, which means that at 600 rpm, the oil-lubricated bearing operates in the hydrodynamic regime in the specific load range up to 2.4 MPa, with a very low coefficient of friction of 0.004. The result is different in the water-bearing lubricated under comparison. The minimum value of the friction coefficient is observed at the specific load of approximately 0.65 MPa, and this is the specific load at which the mixed friction regime starts in the water-lubricated bearing. The friction coefficient's minimum value equals 0.0016 – one fifth of the COF observed in the oil-lubricated bearing at the same specific load. With the specific load increase, one can see a gradual increase in the friction coefficient, which at the specific load of approximately 2.2 MPa becomes equal to that of the oil-lubricated bearing. Despite the operation in the mixed friction regime, the bearing performed very well with no signs of failure or seizure.

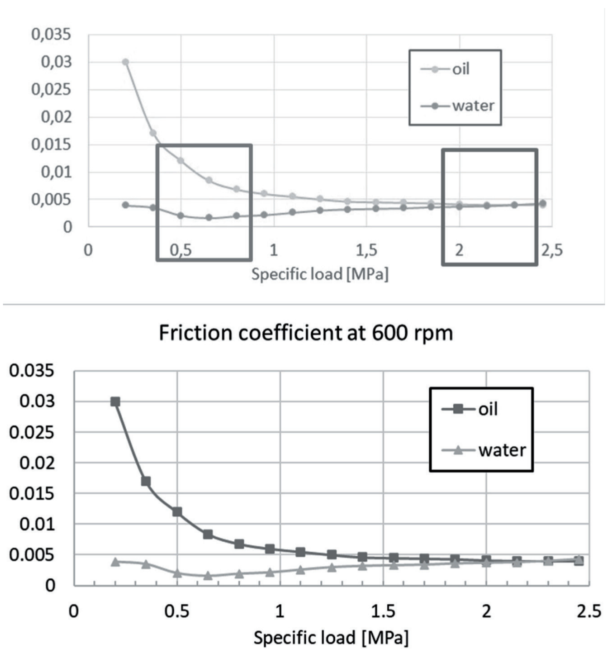

Fig. 3. Friction coefficient in a bearing lubricated with ISO VG 46 oil or water as a function of bearing specific load [L. 5]

Rys. 3. Współczynnik tarcia w łożysku smarowanym olejem ISO VG 46 i wodą w funkcji średnich nacisków **[L. 5]**

The main conclusion from this part of the tests is ambiguous: due to the lower viscosity, friction losses in a water-lubricated bearing can be up to five times smaller than in an oil-lubricated bearing, but once the water-lubricated bearing is to operate at the specific load typical for oil lubricated bearings the friction coefficients are equalised, regardless of the lubricating medium used.

MATERIAL SELECTION ISSUES

Modification of the bearing for water lubrication must comprise the change of materials for both the shaft and the bearing bush. The shaft must be corrosion-resistant, or at least a stainless-steel sleeve mounted on the shaft should be used. The bearing bush material must be suitable for water lubrication, which means that the most popular bearing alloys should be replaced with material better suited to an aqueous environment.

The use of stainless steel is necessary, but unfortunately, it increases the cost of the modification since stainless steel is four to five times more expensive than mild carbon steel The materials successfully used for water lubrication bearings include rubber **[L. 6, 7]**, guaiac (lignum vitae, ironwood) **[L. 8]**, various polymer materials **[L. 9]**, and also metal alloys with the addition of graphite **[L. 10]**, ceramic coatings were also tested in water lubrication with success **[L. 11]**. Also, in the case of materials of the bearing bush, the cost of the alternative material is higher than the traditional tin-based bearing alloys.

Since there are some reports on the good properties of PEEK based composites as alternative bearing materials with oil lubrication **[L. 12]**, it was decided to check their feasibility with water lubrication. PEEK composites are extremely expensive; however, some considerably cheaper substitutes are offered by alternative suppliers. The substitutes are also based on a PEEK matrix with similar additives. Given the relatively brief history of the practical application of these polymers in hydrodynamic bearings, the properties of PEEK-based materials should be checked prior to application. This was the aim of the research reported in this part.

First of all, the physical properties of the materials available on the market were tested, and due to technical possibilities, it was decided to test tensile strength instead of compressive strength because of the possibility of carrying out the tests at elevated temperatures, which reflects operational conditions on the bearing surface in a better way. Tensile strength was tested at room temperature and an elevated temperature, with the use of specimens machined according to **[L. 13]**. The other test, impact strength, was tested with the use of V-notched and unnotched specimens machined according to **[L. 14]**. The measured properties were compared to catalogue data of the original Victrex PEEK 450FC30 taken from the material datasheet **[L. 15]** and with another material based on the original Victrex PEEK, i.e. TECAPEEK PVX Black, according to **[L. 16]**. The results are shown in **Fig. 4** and **Fig. 5**. One can see that the substitute A material is equivalent to TECAPEEK PVX and much superior to the substitute B material. Catalogue properties of an original VICTREX PEEK seem to be considerably better than these of any other materials compared here.

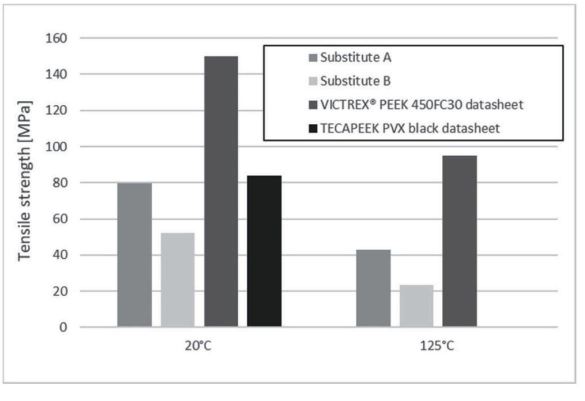

Fig. 4. Tensile strength of various PEEK composites in the room and elevated temperature

Rys. 4. Wytrzymałość na rozciąganie różnych kompozytów na bazie PEEK w temperaturze pokojowej i podwyższonej

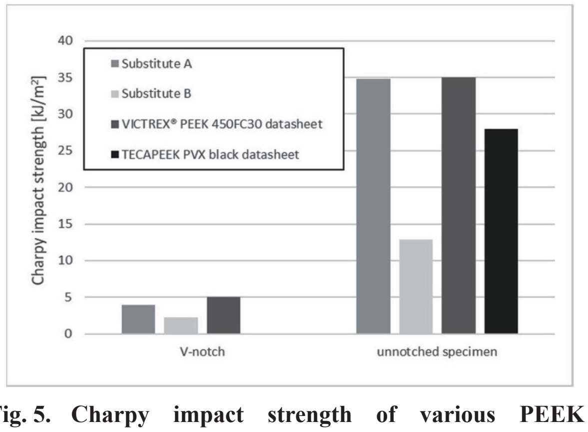

Fig. 5. Charpy impact strength of various PEEK composites tested with the use of V-notched and unnotched specimens

Rys. 5. Udarność różnych kompozytów na bazie PEEK w próbie z próbką z karbem i bez karbu

The other part of the test program was the comparison of tribological properties. Although full film lubrication is a normal condition in the hydrodynamic bearing, and in such conditions bearing material properties are of secondary importance, they become important in the ultimate conditions of bearing overload and film rupture. That is why tests in dry friction were performed in the described research. Samples of three materials were available for testing. One was the material considered to be equivalent to the original Victrex® PEEK and named "original" throughout the rest of the paper; the other two PEEK composites are referenced to as "substitute A", which has been successfully used in some applications, and "substitute B" – which has not been applied before but was considered worth checking due to considerably lower price. The tests were carried out with the use of a PT-3 tribometer **[L. 17]** without lubrication. The ring-on-plane test setup used in the tests is shown in **Fig. 6**. The ring was made from 145Cr6 steel, annealed to HRC 55 and ground to 0.16 µm (Ra parameter). Flat PEEK composite specimens were used as stationary elements (**Fig. 6**), and their roughness (Ra parameter) was equal to 0.32 µm. The tests were run at stepwise increasing load and various rotational speeds until failure.

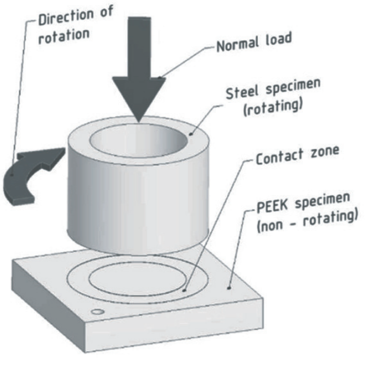

Fig. 6. Ring-on-plane test setup used in tribological testing

Rys. 6. Skojarzenie pierścień-płytka użyte w badaniach tribologicznych

The destroyed samples are shown in **Fig. 7**, and the conditions at which the samples failed or were running safely are collected in **Table 2**. In dry contact tests, the tribological properties of substitute A were superior to both the original material and substitute B. The highest pv factor of safe operation obtained in the tests was 4.57 MPa × m/s for substitute A, 3.06 MPa × m/s for the original

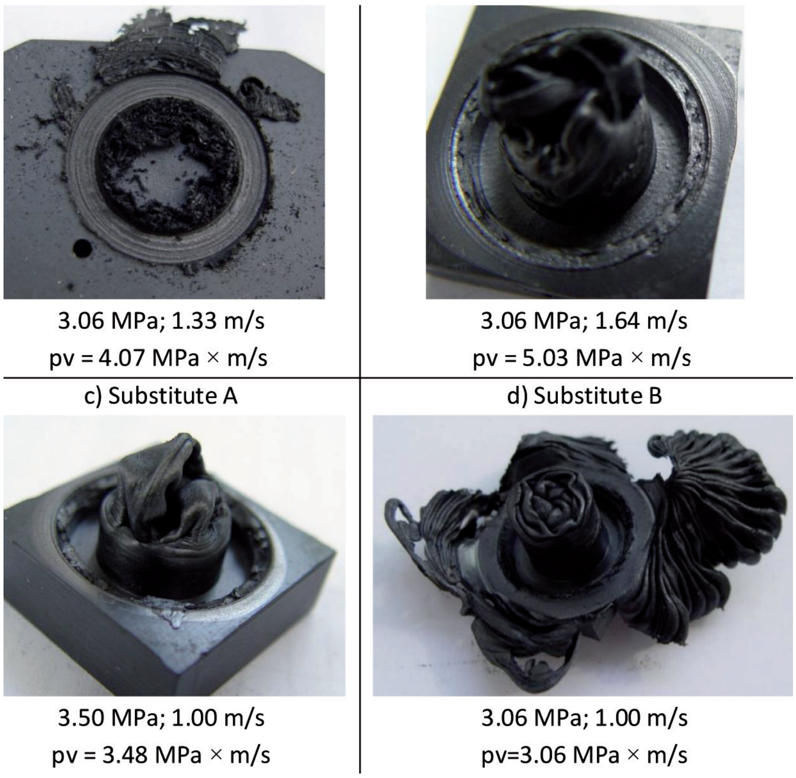

Fig. 7. PEEK specimens after destructive testing
Rys. 7. Próbki PEEK po próbach niszczących

Table 2. Results of tribological tests
Tabela 2. Wybrane wyniki testów tribologicznych

Material	pv factor of failure [MPa × m/s]	pv factor of safe operation [MPa × m/s]
Original material	4.07 (3.06 MPa and 1.33 m/s)	3.06 (3.06 MPa and 1 m/s)
Substitute A	3.50 (3.50 MPa and 1.00 m/s)	4.57 (3.06 MPa and 1.33 m/s)
	5.03 (3.06 MPa and 1.64 m/s)	
Substitute B	3.06 (3.06 MPa and 1.00 m/s)	2.85 (2.14 MPa and 1.33 m/s

material and 2.85 MPa × m/s for substitute B. One has to realise, however, that these results are based on a limited number of tests and that in order to determine the limiting pv factor, allowable specific load and sliding speed, many repetitions and more thorough testing would be necessary.

Apart from mechanical and tribological testing, analysis of the structure of the delivered composite polymer material was carried out – two techniques were used scanning electron microscope (SEM) and optical (light) microscope (LM). The observations of the fracture surfaces of the PEEK specimen were performed using the scanning microscope at accelerating voltages: 10 kV and 15 kV, with the use of Thermo Scientific Phantom ProX 6.

High adhesion forces in composites indicate good compatibility of the component materials, which is related to the proper preparation (sizing) of the components. The increased roughness of the carbon fibres is also an important issue, as it increases the surface area of the force interactions between the matrix and the fibre. The microstructure of the specimens obtained from the original PEEK composite samples taken from the breakthrough cross section after impact testing is shown in **Fig. 8 a**. Carbon fibres of the diameter of 8.16 μm ±0.66 μm were observed in the sample, the length of the carbon fibre used for reinforcement was ~200.

A large amount of the matrix material retained around the carbon fibres was observed on the fracture of the original material (**Fig. 8a**) and substitute material A (**Fig. 8b**). This indicates the nature of the cohesive fracture, i.e., the fracture occurred in the matrix (PEEK); thus, there was no debonding and disengagement of the fibres from the plastic material. This is a desirable phenomenon in composites because potentially the weakest area in composites is the fibre/matrix interface. Increasing the adhesion forces between the phases (fibre/matrix) makes it possible to transfer more stress from the matrix to the fibre, resulting in higher composite strength.

In opposition to the above findings were the conclusions concerning substitute material B. Carbon fibres were shorter by 60% in comparison to both the original material and substitute A. Shorter fibres contributed to a reduction in the strength (weakening) of the composite. At the breakthrough of the tested substitute B, shown in **Fig. 8c**, the carbon fibres exposed from the matrix (PEEK) and the voids in the matrix material left by the fibres extracted upon fracturing were observed. Debonding of the fibre from the matrix was observed and shown. Thus, low adhesion between the carbon fibre (reinforcement) and the PEEK plastic (matrix) was proven – a structural flaw responsible for the reduction of the mechanical strength. Poor preparation of the fibre may cause the reason for the low adhesion of the fibre to the matrix prior to adding it to the composite within the manufacturing process.

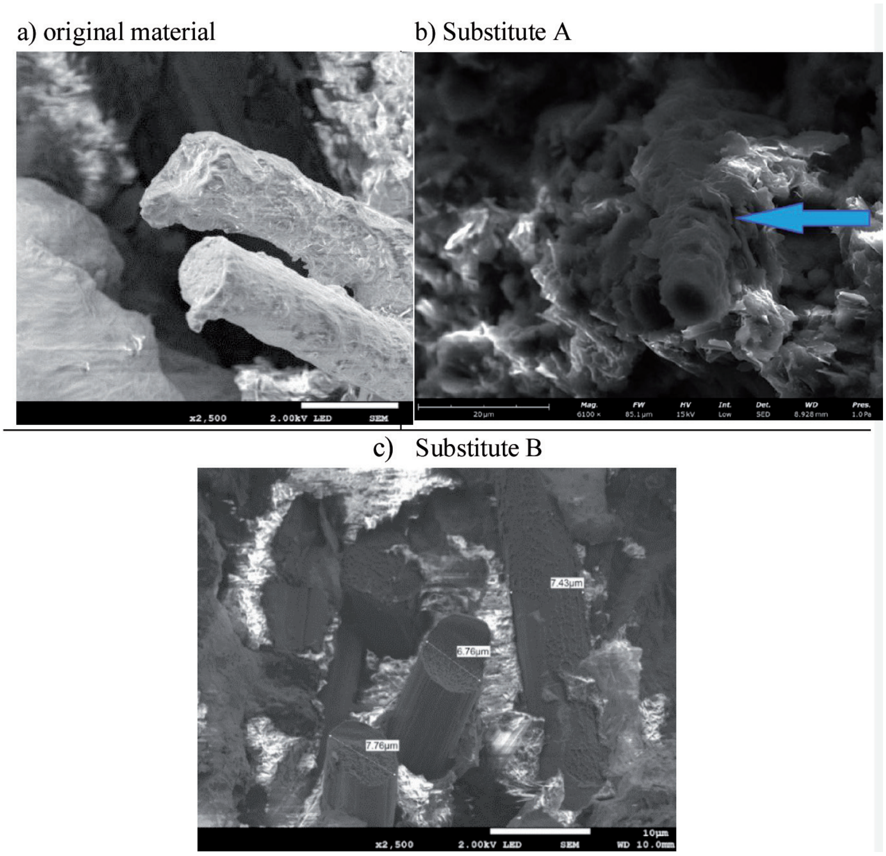

Fig. 8. Microstructure (SEM) of the breakthrough of: a) original material, b) substitute A, c) substitute B after the Charpy test

Rys. 8. Obraz SEM mikrostruktury przełomu próbek po próbie udarności: a) materiał oryginalny, b) zamiennik A, c) zamiennik B

DISCUSSION AND CONCLUSIONS

The paper presents the problems that may be encountered when applying water-lubricated bearings as an ecological retrofit to a machine originally equipped with oil-lubricated bearings. The main conclusion on the potential profits of the application of a journal bearing with water lubrication is ambiguous. On the one hand, the tested bearing was operating with no problem, even at a high specific load in the mixed lubrication regime. On the other hand, benefits in friction losses are not obvious because, due to lower viscosity, friction losses can be up to five times smaller than in an oil-lubricated bearing, but once the water-lubricated bearing is to operate at the specific load typical for oil lubricated bearings the losses become the same.

Another difficulty lies in material selection. Due to the high prices of PEEK composites, it is natural to seek substitute materials from different suppliers, but, as was shown in the tests, both the mechanical and tribological properties of the substitutes can be much worse than those declared by the manufacturer. Inferior mechanical and tribological properties were explained by a probable deficiency in the manufacturing process of the material resulting in poor adhesion between the carbon fibre, serving as the reinforcing phase in the composition polymer matrix-based structure. These findings show that before using a substitute bearing material, it is highly recommended to carry out independent testing of the properties of the selected substitute material.

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