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# THE INFLUENCE OF OILS ON THE SCUFFING OF CONCENTRATED FRICTION JOINTS WITH LOW-FRICTION COATED ELEMENTS

# WPŁYW OLEJÓW NA ZACIERANIE ELEMENTÓW Z POWŁOKAMI NISKOTARCIOWYMI SKOJARZONYMI W STYKU SKONCENTROWANYM*

*The paper presents the results of four-ball scuffing tests for the following oils: polyalphaolefine oil (PAO 8), refined rapeseed oil (RzR), as well as mineral and synthetic oils of GL5 API performance level. Three material combinations of friction joints were investigated, with the upper ball material as a variable. In the research, 100Cr6 bearing steal balls were used. The tests were carried out for uncoated and low-friction coated balls. Two PVD coatings were used: a-C:H:W and $MoS_2$/Ti. The research results were compared with the outcome from the tests of the reference mineral oil (RL 219). The influence of oils on friction joint scuffing characteristics were determined using the scuffing load $P_t$ and limiting pressure of seizure poz, obtained by means of the four-ball method with continuously increasing load. The obtained results indicate that, in case of concentrated friction joints with low-friction coated elements, the influence of selected oils on scuffing depends on the type of PVD coating used. The research findings also show the significant practical effect of aforementioned PVD coatings deposition on steel elements of friction joints, which is the interception of the anti-scuffing function of the classical extreme pressure (EP) oil additives by the coating. Due to that fact, the usage of such coatings makes it possible to reduce the concentration of EP additives, resulting in more environmental friendly oils.*

***Keywords***: *scuffing, seizure, oils, coatings, four-ball tester.*

*W artykule przedstawiono wyniki badań zacierania modelowego, czterokulowego węzła tarcia, smarowanego olejami bez dodatków smarnościowych: mineralnym olejem wzorcowym (RL 219), syntetycznym (PAO 8), rafinowanym olejem rzepakowym (RzR), oraz dwoma olejami handlowymi z dodatkami klasy GL5 na bazie mineralnej i syntetycznej. Przebadano trzy skojarzenia materiałowe, w których zmienną stanowił materiał kulki górnej. Zastosowano kulki ze stali łożyskowej (100Cr6) bez powłoki oraz z niskotarciowymi powłokami: a C:H:W (WC/C) oraz $MoS_2$/Ti, osadzonymi metodą PVD. Rezultaty badań porównano z wynikami otrzymanymi dla mineralnego oleju wzorcowego (RL 219). Dokonano oceny wpływu oleju na zacieranie węzła tarcia, wykorzystując wskaźniki obciążenia zacierającego $P_t$ oraz granicznego nacisku zatarcia poz, otrzymane przy zastosowaniu metody z narastającym obciążeniem. Stwierdzono, że wpływ rodzaju oleju na zatarcie elementów stalowych pokrytych powłokami PVD jest zależny od rodzaju powłoki. Ważnym efektem praktycznym jest też wskazanie, że powłoki PVD nanoszone na elementy stalowych systemów tribologicznych, przejmują funkcje klasycznych, nieekologicznych na ogół, dodatków smarnościowych (EP), pozwalając na redukcję ich zawartości w środkach smarowych.*

***Słowa kluczowe***: *zacieranie, zatarcie, oleje, powłoki, aparat czterokulowy.*

## 1. Introduction

Heavily loaded friction joints, such as gears, rolling bearings, and cam-follower units are neuralgic parts of engines and transmissions, and millions of these parts are produced each year. In recent years, there has been a considerable development in the area of the construction of machine parts in the direction of size and energy-consumption reduction. Unfortunately, the size reduction is followed by an increase in the contact stresses, which results in higher risk of scuffing and may lead to machine failure.

The introduction of new technological solutions is inevitable, because the producers of heavily loaded machine parts predict that further increase in the durability by means of conventional technologies, like those connected with modelling of the mechanical strenght of the base material of gears (mainly steel), is practically impossible [6]. A similar problem can also be observed in the field of lubricant modification, especially in the case of an increase in the concentration of active anti-scuffing (EP) additives, which lead to a significant decrease in the resistance to pitting of the friction joints [27]. The research carried out by the authors [17, 29] indicate that the deposition of thin antiwear PVD/CVD (physical vapour deposition/chemical vapour deposition) coatings on machine elements by means of vacuum methods represent a promising direction in the aspect of machine life extension. In recent years, the antiwear PVD/CVD coatings have revolutionised the market of cutting and forming tools. It is estimated that approx. 80% of the currently used cutting tools are coated in order to increase their durability.

The typical coatings that are used for the tools cannot be deposited on the friction joints elements, due to the insufficient resistance to fatigue wear (pitting) [23]. Only in the case of low-friction thin hard coatings, such as WC/C and $MoS_2$/Ti, the resistance to pitting can be

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** obtained on a similar level as in the case of steel material, even under lubrication with oils without additives.

The application of coating, even on only one of the friction joint elements, results in the change in the chemical composition of the contacting materials, in the level of residual stresses, and in surface physical structure, leading to a change in the relation between the machine elements and the lubricant. The range of PVD/CVD coatings application is limited by the lack of knowledge about the interaction between coatings and components of lubricants. Unfortunately, most research on the characteristics of wear mechanisms for coatings have been performed under conditions of dry friction. Therefore, the obtained results cannot be referred to heavily loaded, lubricated friction joints [2, 11, 12, 15, 26]. The problem of coating applications on machine parts is a relatively new, so the research findings available in literature, related to the physical and chemical interactions between the lubricants and the coated elements, are incomplete and ambiguous [16, 22]. The processes that occur in the contact zone between the coating and the lubricant components are insufficiently identified, especially when the friction joint working under extreme conditions is considered [3, 8, 16, 28]. Some of these interactions might be modified by the proper selection of lubricant additives; however, the selection requirements developed for steel friction joints do not apply to tribosystems in which at least one element is coated.

The application of coatings on machine parts is in the focus of interest of many leading research institutes worldwide [10, 20, 21]. In Europe, investigation on coating deposition on gears for the increase of scuffing resistance was realized in the COST 532 Action EU framework [1] and other projects. In the USA, similar works were part of NASA's research field [7].

In the literature, there are many references to the application of diamond-like coatings (DLC) on the gear teeth, the units of the camshafts (pivots), pushers and piston rings [4, 5, 9]. The coatings are mainly used on parts working with uncoated elements and subjected to scuffing [Fig.1].

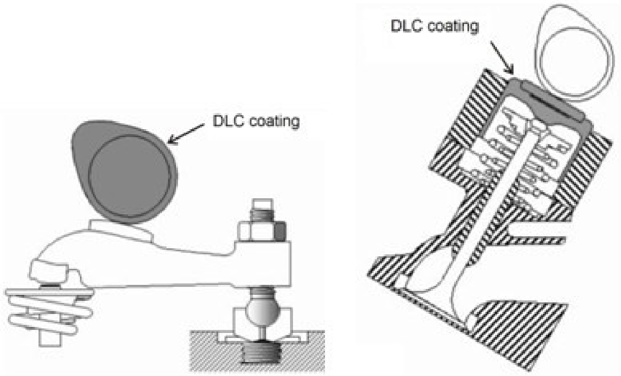



*Fig. 1. The images of machine units with coated elements*

## 2. Test method

For evaluation of scuffing resistance, a four-ball tribosystem was employed [11-13]. Test balls were made of 100Cr6 bearing steel with a diameter of 12.7 mm (0.5 in.) with $R_a$ surface roughness of 0.032 and 60±2 HRC hardness. The four-ball tribosystem is presented in Fig. 2.

The three stationary bottom balls (2) are fixed in the ball pot (4) and pressed against the top ball (1) under the continuously increasing load P. The top ball is fixed in the ball chuck (3) and rotates at the constant speed n. The tribosystem is immersed in the tested lubricant.

a) b)

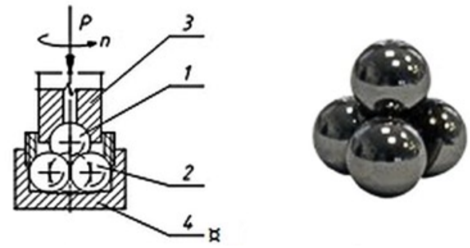



*Fig. 2. Model four-ball tribosystem for testing scuffing: a) tribosystem: 1 - top ball, 2 - lower balls, 3- ball chuck, 4 - ball pot, b) photograph*

During the run, the curve of friction torque is recorded until seizure occurs or a load of 7200 N is achieved.

The investigation was performed under following conditions:

- Shaft rotational speed [rpm]: 500
- Sliding speed [m/s]: 0.19
- Speed of load growth [N/s]: 409
- Maximum load [N]: 7200±100
- Initial load [N]: 0
- Starting temperature [°C]: approx. 20
- Min. number of tests: 3 per each tested friction joint.

An example of friction torque course ($M_t$) obtained at the continuously increasing load (P) is shown in Fig. 3.

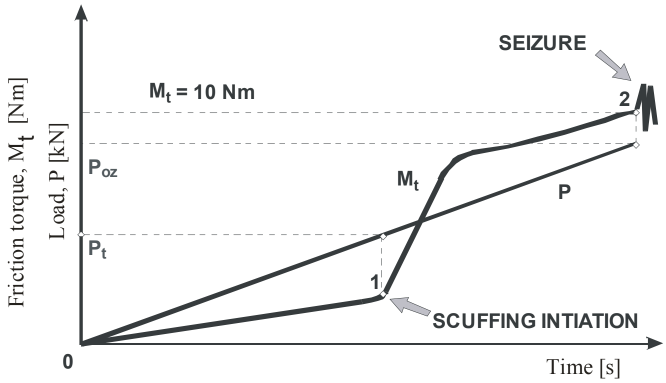



*Fig. 3. An example of simplified friction torque curve ($M_t$) obtained under continuously increasing load (P): 1 – scuffing initiation, 1-2 – scuffing propagation, 2 – seizure*

Scuffing initiation occurs at the time of a sudden increase in the friction torque – Point 1. The load at this moment is called the scuffing load and is denoted as $P_t$ (according to the standard [18]). In accordance with the test method, the load still increases (over the value of $P_t$) until seizure occurs (i.e. friction torque exceeds 10 Nm - Point 2). The load at this moment is called the seizure load and is denoted as $P_{oz}$. If 10 Nm is not reached, the maximum load (c.a. 7200 N) is considered to be the seizure load (even though there is no seizure) [17].

The $p_{oz}$ - limiting pressure of seizure is calculated from the following equation (1):

$$p_{oz} = 0{,}52 \frac{P_{oz}}{d^2} \tag{1}$$

Where:

$P_{oz}$ – the load P under which the seizure occurs,
d – the average diameter of wear scar on the lower balls.

## 3. The aim and the subjects of the study

The aim of the study was to determine the influence of oils on the scuffing characteristics of steel friction joints and friction pairs with elements with deposited low-friction coatings. The tested friction joints were lubricated with the following oils: RL 219 mineral reference oil, PAO 8 synthetic polyalfaolephin oil, RzR rapeseed refined oil, and two API GL5 class commercial oils containing EP additives (GL5m mineral and GL5s synthetic). The physiochemical properties of these oils are presented in the Table 1.

*Table 1. The physiochemical characteristic of investigated oils*

| Property | Unit | Oil | | | | |
|---|---|---|---|---|---|---|
| | | RL 219 | PAO 8 | RzR | GL5m | GL5s |
| Viscosity at 40 °C | mm²/s | 49.31 | 47.04 | 25.68 | 40.00 | 81.00 |
| Viscosity index | - | 99 | 140 | 213 | 106 | 194 |
| Density at 15 °C | g/ml | 0.874 | 0.832 | 0.921 | 0.880 | 0.879 |
| Flash point | °C | 225 | 260 | 332 | 220 | 205 |

The tests were done for uncoated and low-friction coated balls. Two PVD coatings were used - WC/C and MoST. The WC/C coating is a DLC type representing a-C:H:Me group. The coating consisted of an elemental Cr adhesion layer adjacent to the steel substrate, followed by an intermediate transition region consisting of alternating lamellae of Cr and WC, and an outermost W containing a hydrocarbon (a-C:H:W) layer. The composition of the outermost a-C:H:W layer, in atomic percentage, is approximately 12% W, 70% C, 15% H, and 3% Ni. The a-C:H:W coating was deposited using PVD (Physical Vapour Deposition) by reactive sputtering. MoST is the commercial name of a low-friction composite coating $MoS_2$/Ti. The $MoS_2$/Ti coating is deposited by DC Magnetron Sputtering using a CFUBMSIP process (closed field unbalanced magnetron sputter ion plating). The coating procedure starts with ion cleaning, followed by a 70 nm Ti layer, a 200 nm $MoS_2$/Ti multilayer, a 900 nm $MoS_2$/Ti (non-multilayer) and a last step of a 50 nm layer of $MoS_2$ giving the characteristic surface colour.

## 4. The results of scuffing tests

The resistance to scuffing was determined by calculating: $P_t$ scuffing load and $p_{oz}$ limiting pressure of seizure. The $p_{oz}$ indirectly characterizes the resistance to wear in sliding motion. The higher the $P_t$ and $p_{oz}$ indicators are, the higher the resistance to scuffing and seizure is. The $P_t$ and $p_{oz}$, shown in the diagrams were calculated on the bases of at least three test runs for each investigated friction joint; whereas, the diagrams showing the characteristics of friction torque present only one of selected results from each tested friction joint.

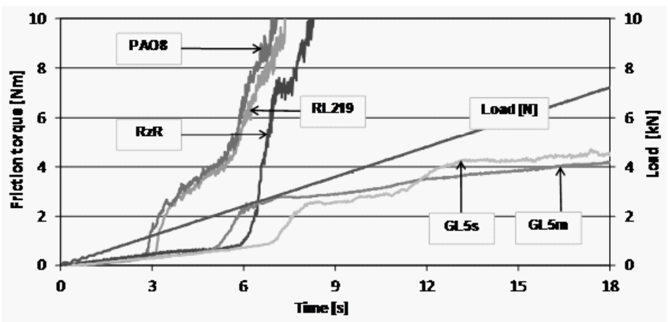



*Fig. 4. Graphs of friction torque for steel-steel couples lubricated with tested oils*

The friction torque lines obtained for the steel-steel friction joint lubricated with tested oils are shown in Fig. 4.

As it is shown in the graph, in the case of steel-steel (100Cr6-100-Cr6) friction pair, only the commercial GL5 quality class oils prevent the friction joint from seizure. It is because these oils contain EP (Extreme Pressure) anti-scuffing additives and are designed to lubricate the heavily loaded steel pairs.

The other base oils (without additives) do not prevent seizure; however, the vegetable oil demonstrates a level of resistant to scuffing initiation as high as the commercial synthetic oil, significantly exceeding the $P_t$ obtained for GL5m mineral oil. It is important to remark that the rapeseed oil has the lowest viscosity at 40°C among all tested lubricants.

The average values of $P_t$ scuffing load obtained for steel friction joints, under conditions of lubrication with investigated oils, are presented in Fig 5.

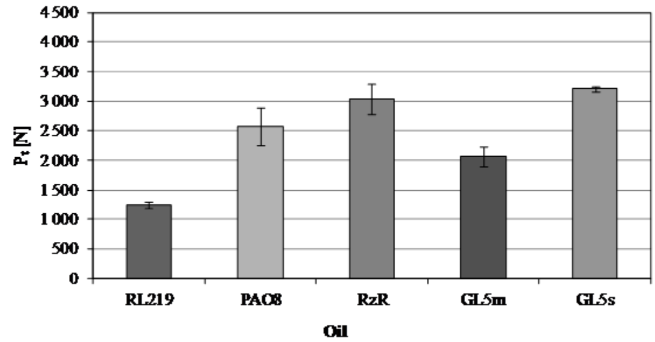



*Fig. 5. The $P_t$ scuffing load for steel-steel friction joints lubricated with tested oils*

It should be emphasized that, although the steel-steel friction joint lubricated with RzR oil has a higher value of $P_t$ in comparison with friction joint lubricated with mineral commercial GL5 oil, the rapeseed oil do not provide full protection against scuffing.

The average values of $p_{oz}$ limiting pressure of seizure, obtained for steel friction joints under conditions of lubrication with investigated oils are presented in Fig 6.

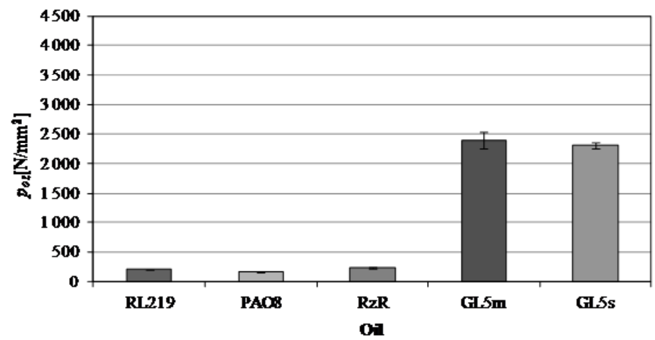



*Fig. 6. The $p_{oz}$ limiting pressure of seizure for steel-steel friction joints lubricated with tested oils*

As it is shown in the Figures 4 and 6, the average values of $p_{oz}$ limiting pressure of seizure are nearly similar for all three base oils. Due to the fact that there was no seizure observed for both GL5 oils, the maximum $P_{oz}$ value was taken to account for $p_{oz}$ calculating, giving approximate information about the wear, which is slightly lower for the friction joint lubricated with synthetic GL5s oil.

The four-ball tests were also performed for all investigated oils, lubricating the friction joint with three lower balls of steel and the upper ball coated with WC/C thin, hard, low-friction coating. The friction torque lines obtained for the WC/C-steel friction joint lubricated with tested oils are shown in Fig. 7.

As the friction torque graphs indicate, the WC/C-steel pairs lubricated with GL5 oils and the synthetic base oil did not undergo seizure. The introduction of a WC/C coated upper ball to the tribosystem results in a significant increase in the resistance to scuffing of all couples lubricated with tested oils. As it is shown in Fig. 6, the friction torque lines for both synthetic oils, are almost overlapped, which can be interpreted as taking over of the EP additives action by the WC/C coating. This feature of WC/C confirms the results from the earlier, low-friction coating research [14, 29].

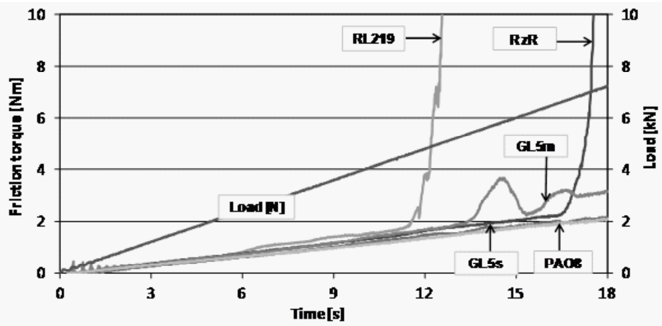



*Fig. 7. Graphs of friction torque for WC/C-steel couples lubricated with tested oils*

The average values of $P_t$ scuffing load obtained for WC/C-steel friction joints under conditions of lubrication with investigated oils are presented in Fig. 8.

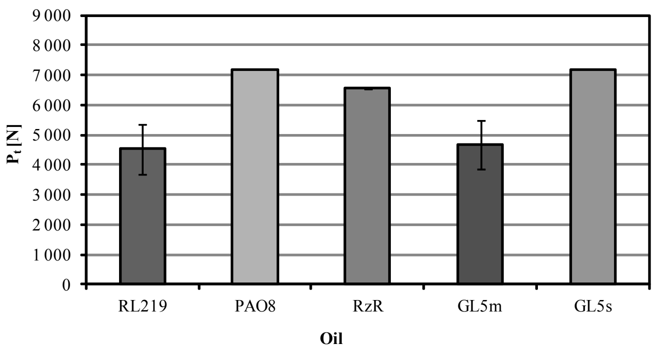



*Fig. 8. The $P_t$ scuffing load for WC/C-steel friction joints lubricated with tested oils*

The $P_t$ scuffing load for WC/C-steel for the mineral oil is four times higher than for the steel tribosystem. In case of rapeseed oil, the increase is twofold. The highest $P_t$ value was obtained for the both synthetic oils – base and commercial. Considering the scuffing load value for the WC/C-steel couple lubricated with base and commercial mineral oils, the high spread of results as compared to the remaining oils can be observed. Interestingly, despite the increase in scuffing load, the friction joint lubricated with mineral oil did not achieve anti-seizure protection. In contrast to the synthetic oils, the effect of the action of EP additives is very clear in case of mineral oils. The case of vegetable oil is also interesting, because, for WC/C- steel friction joint, a difference in $P_t$ of 1.5 times can be observed as compared to the reference oil lubricated joint, even in spite of the kinematic viscosity of rapeseed oil, which is substantially lower.

The average values of $p_{oz}$ limiting pressure of seizure, obtained for WC/C-steel friction joints, under conditions of lubrication with investigated oils, are presented in Fig. 9.

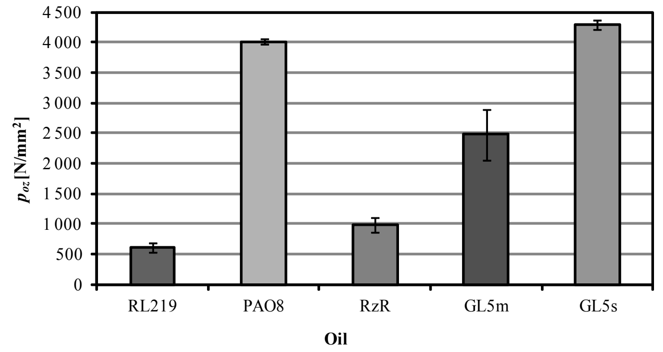



*Fig. 9. The $p_{oz}$ limiting pressure of seizure for WC/C-steel friction joints lubricated with tested oils*

The results indicate that both synthetic oils represent the highest resistance to wear with a slight advantage for commercial GL5s oil.

Apart from steel-steel and steel-WC/C friction joints, the four-ball tests were also performed for all investigated oils, lubricating the friction joint with three lower balls of steel and the upper ball coated with $MoS_2$/Ti coating. The friction torque graphs obtained for the $MoS_2$/Ti-steel friction joint lubricated with tested oils are shown in Fig. 10.

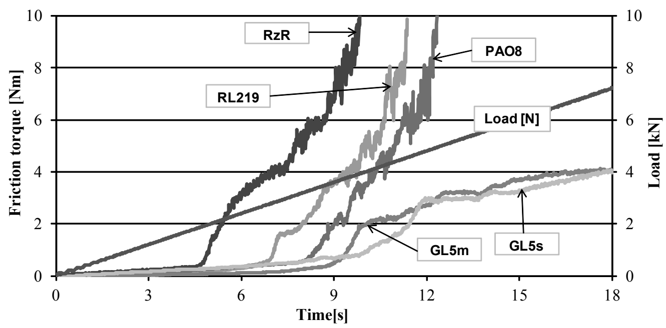
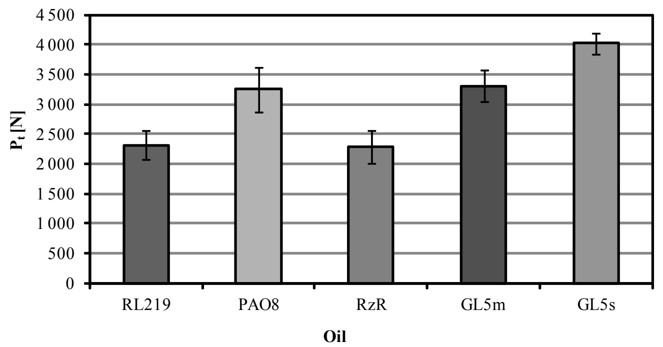



*Fig. 10. Graphs of friction torque for $MoS_2$/Ti-steel couples lubricated with tested oils*

The lines of friction torque for $MoS_2$/Ti-steel couples indicate that, in comparison with the steel reference friction joint, there is an observable improvement in the resistance to scuffing in almost all tested cases. The only exception is the friction joint lubricated with rapeseed oil.

The average values of $P_t$ scuffing load and $p_{oz}$ limiting pressure of seizure obtained for $MoS_2$/Ti-steel friction joints under conditions of lubrication with the investigated oils are presented respectively in Figs. 11 and 12.

The differences in $P_t$ values in all tested cases do not exceed 50%. Considering $p_{oz}$ limiting pressure of seizure, there is a certain improvement in protection against seizure; however, it is much lower




*Rys. 11. The $P_t$ scuffingload for $MoS_2$/Ti-steel friction joints lubricated with tested oils*

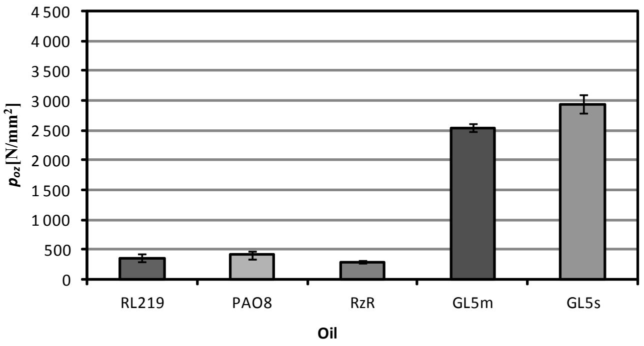



*Fig. 12. The $p_{oz}$ limiting pressure of seizure for $MoS_2$/Ti-steel friction joints lubricated with tested oils*

than in the case of WCC-steel friction joint, especially lubricated with synthetic base oil.

For $MoS_2$/Ti-steel friction joint, the best anti-scuffing and anti-seizure protection is provided by lubricating the tested friction joint with the GL5 commercial oils.

## 5. Conclusions

The obtained results indicate that, in the case of the tested concentrated friction joints, the role of selected oils on scuffing is crucial. The influence of the oil on the scuffing wear of friction joints with PVD coated steel elements depends on the type of deposited coating. The introduction of a friction joint element with a low-friction coating favourably affects most of the obtained scuffing characteristics, which is confirmed by following observations:

1. In the case of steel-steel friction joint, only the commercial oils provide the friction joint with an effective protection against seizure. The vegetable oil ensures a longer time before scuffing initiation in comparison to mineral-based commercial oil; however, in the consequence of the lack of extreme pressure additives, seizure of the friction joint lubricated with RzR takes place under only a slightly higher load than in the case of the mineral-based reference oil and PAO 8 oil. The characteristics of scuffing for the friction joint lubricated with PAO 8 and RL 219 overlap, demonstrating the lowest scuffing protection among tested lubricants.
2. The use of a-C:H:W coating improves scuffing resistance in all tested cases. For the vegetable oil and mineral commercial oil, the scuffing load is nearly two times higher; however, the protection from seizure is not provided. The most significant change is observed for the friction joint lubricated with PAO 8, where the scuffing characteristic overlaps with the one obtained for the synthetic commercial oil containing the EP additives. **It follows that the coating takes the role of the additives**, which is convergent with the results obtained by the authors in their previous works.
3. The application of $MoS_2$/Ti coating has a negative result in the form of scuffing initiation acceleration for the friction joint lubricated with vegetable oil. On the other hand, the friction joints lubricated with PAO 8 demonstrates approximately a twofold increase in both the scuffing load and in limiting the load of seizure, in comparison with uncoated friction joint. The $MoS_2$/Ti coating also improves a level of the protection from seizure for the friction joints lubricated with the tested commercial oils.
4. The highly important demonstrated and practical effects of this research are that the PVD coatings deposited on steel elements of tribosystems intercept the function of most commonly used EP additives and that the usage of such coatings makes it possible to reduce the oil additive concentrations, resulting in more environmental friendly oils.

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