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A NEW TEST FOR THE QUALITATIVE AND QUANTITATIVE DISCRIMINATION BETWEEN AUTOMOTIVE TRANSMISSION AND AXLE OILS

NOWA METODA JAKOŚCIOWEGO I ILOŚCIOWEGO RÓŻNICOWANIA SAMOCHODOWYCH OLEJÓW PRZEKŁADNIOWYCH

Key words:

four-ball test, scuffing, seizure, automotive gear oil, API GL performance level

Słowa kluczowe:

metoda czterokulowa, zacieranie, zatarcie, samochodowy olej przekładniowy, klasa jakościowa API GL

Summary

In this work, the authors analyse the possibility of using a new test method, called *the method for the determination of the limiting pressure of seizure* p_{oz}, to differentiate between the API GL performance levels of automotive

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transmission and axle oils from the point of view of their EP properties. The new test is performed under conditions of the scuffing of the four-ball tribosystem, initiated by the linearly increasing load, until seizure occurs. In numerous publications, it has been shown that the new test has many pros in comparison with standardised tests used for the assessment of extreme-pressure (EP) properties of lubricants. It exhibits a better resolution and is quicker, cheaper, and its precision is comparable to the precision of the standardised tests of EP properties of lubricants.

A representative group of the automotive gear oils of the API GL-1 to GL-5(LS) performance level was tested using a four-ball tribotester with the sliding tribosystem. It has been shown that the method for the determination of the limiting pressure of seizure p_{oz} makes it possible to differentiate between most of the API performance levels of the automotive gear oils – both qualitatively (i.e. by the analysis of the friction torque curves) and quantitatively (on the basis of p_{oz} values); although, the qualitative way is more effective (better resolution) than the quantitative one.

Because the new test method reduces the cost (simple, inexpensive test specimens) and the duration of the testing, it can be applied in R&D industrial labs to verify the quality of automotive gear oils.

INTRODUCTION

Various reports indicate that, in Europe, automotive transmission and axle oils constitute 75% of the automotive gear oil production in comparison to only 25% of the market occupied by automatic transmission fluids (ATFs).

The specifications and requirements concerning automotive transmission and axle oils is provided in API Publication 1560. It divides such gear oils into 7 basic service designations (performance levels). Currently on the market, one can find the gear oils of the following performance levels: API GL-1, GL-3, GL-4, GL-4/GL-5, GL-4/GL-5/MT-1, GL-5, GL-5/MT-1, GL-5(LS), and GL-6. It can be generally stated that the higher GL number of the gear oil, the more difficult are the service conditions it is intended for. Therefore, the API GL-1 oils are used for the lubrication of manual transmissions operating under mild conditions, GL-3 for manual transmissions operating under moderate to severe conditions, GL-4 for synchronised manual transmissions of European cars, GL-5 for hypoid gears in axles, GL-5/MT-1 for non-synchronised manual transmissions in buses and heavy-duty lorries, GL-5 (LS) for limited-slip differentials in axles, and GL-6 for hypoid gears (in axles) with a very high pinion offset.

To prove that a candidate automotive gear oil meets the requirements of a given API GL performance level, it is necessary to carry out various tests, both tribological and physiochemical ones specified in various standards. For example, SAE J2360 concerns the tests required to check whether the gear oil fulfils the service requirements of the API GL-5/MT-1 level. One of the most important tests is commonly referred to as the L-42 scoring test, performed on the rear axle of a lorry. The test aims at the assessment of the extreme-pressure (EP) properties of the tested oil at a high rotational speed and shock loading and at a high working temperature. Another test of the EP properties of a gear oil is also expensive, but not as much as the L-42. This is the gear scuffing test known as FZG A/8,3/90, performed on special test spur gears, and included in the new standard – ASTM D 5760 – related to the API GL-5/MT-1 performance level.

In view of very high costs of especially L-42 test, some research institutes seek less expensive and quicker tests carried out on simple model tribosystems **[L. 1, 2]** or develop new tests of EP properties of gear oils **[L. 3, 4]**.

The authors have developed a new method for testing EP properties of lubricants. In numerous publications, it has been shown that the new test has many pros in comparison with standardised tests. It exhibits a better resolution and is quicker, cheaper, and its precision is comparable to the precision of the standardised tests of EP properties of lubricants **[L. 5]**.

This work concerns the assessment of the possibility of using the new test for qualitative and quantitative discrimination between API GL performance levels of automotive transmission and axle oils.

EXPERIMENTAL

New test

According to the new test method, called *the method for the determination of the limiting pressure of seizure* p_{oz}, the lubricant is tested in a four-ball tribosystem, under the conditions mentioned below, at continuously increasing load starting from a value close to 0. Friction torque is observed until seizure occurs. It is assumed that seizure occurs when 10 Nm friction torque is exceeded.

Test conditions:

– rotational speed	500 rpm
– speed of continuous load increase	409 N/s
– initial load	≈ 0 N
– maximum load	7400 N
– ambient temperature	20 ± 5°C
– lubrication	dip.

A simplified friction torque curve (M_t) is shown in **Fig. 1**.

The load at Point 1, at which the friction torque drastically increases, is called the scuffing load and is denoted as P_t. The load still increases until Point

2 (seizure) is attained, which referred to as exceeding the permissible friction torque of 10 Nm. The load at this moment is called the "seizure load" and is denoted as P_{oz}. During the run, the friction torque M_t is measured, and its curve is later analysed to assess the character of the scuffing propagation. Then, the API GL performance level of the tested oil is identified based on the scuffing propagation character. This is the **qualitative** discrimination between the gear oils.

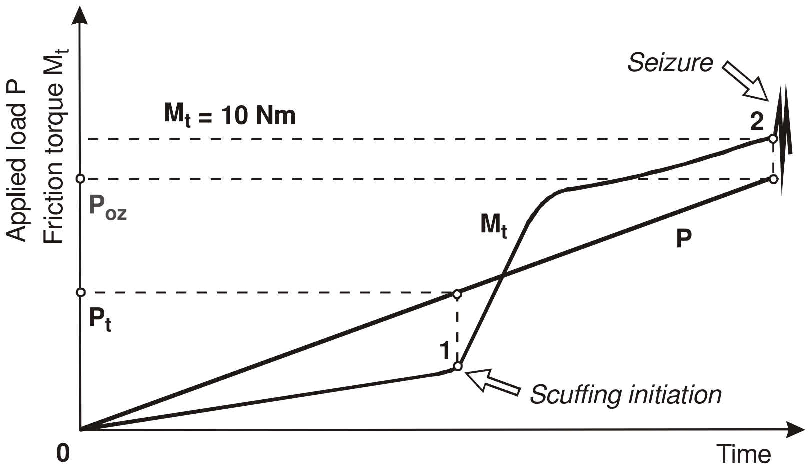

Fig. 1. The simplified friction torque curve (M_t) obtained at continuously increasing load (P): 1 – scuffing initiation, 1–2 – scuffing propagation, 2 – seizure

Rys. 1. Uproszczona krzywa momentu tarcia (M_t) uzyskana w warunkach rosnącego w sposób liniowy obciążenia (P): 1 – inicjacja zacierania, 1–2 – propagacja zacierania, 2 – zatarcie

After the test, the diameters of the wear scars on the bottom balls are measured and the average value d is calculated. Then, taking into account the seizure load P_{oz} or the maximum attained applied load, the limiting pressure of seizure p_{oz} is determined from Eq. (1):

$$p_{oz} = 0.52 * P_{oz} / d^2 \text{ [N/mm}^2\text{]} \quad (1)$$

The p_{oz} values are used for **quantitative** discrimination between gear oils. The higher p_{oz}, the better are the extreme-pressure (EP) properties of the tested oil.

Test equipment and samples

The new test is carried out using a modified four-ball tester, denoted as T-02, or its newest version – T-02U. This apparatus was designed and is manufactured at ITeE – PIB. Because of the modification of the loading system, it is possible to increase the load continuously during test runs. This unique feature is necessary for the realisation of the new test procedure. The motor control unit automatically turns off the machine at seizure, when the maximum friction torque (10 Nm) has been exceeded.

Test balls are chrome alloy bearing steel with diameters of 12.7 mm (0.5 in.). Surface roughness does not exceed R_a = 0.032 µm, and hardness is between 60 to 65 HRC.

Oils tested

About 50 automotive transmission and axle oils were selected for testing and divided into six groups of API GL performance levels – **Tab. 1**. The table includes: API GL performance levels (basic or grouped), the type of the lubricating additives and base oil used in each group, ranges of kinematic viscosities at 100ºC (ν_{100}), and ranges of viscosity indexes (VI).

Almost all of the oils tested were commercial products.

RESULTS AND DISCUSSION

Qualitative discrimination

Comprehensive results concerning the qualitative discrimination of the automotive transmission and axle oils are presented in the authors' work **[L. 6]** and monograph **[L. 7]**. Therefore, here only the summary of the most interesting findings will be shown.

Friction torque curves, reflecting scuffing propagation, typical of the tested gear oils, are presented in **Fig. 2**.

Table 1. Short characteristic of the tested gear oils
Tabela 1. Wybrane właściwości badanych olejów

API GL performance level	Lubricating additives	Base oil type	ν_{100} [mm^2/s]	VI
GL-1	None	Only mineral	14.6 – 31.4	92 – 103
GL-3	Antiwear (AW)	Only mineral	13.6 – 15.0	90 – 125
GL-4	Extreme-pressure (EP)	Mineral or synthetic	8.2 – 30.7	94 – 203
GL-4/GL-5 and GL-4/GL-5/MT-1	Extreme-pressure (EP)	Mineral or semi-synthetic or synthetic	8.8 – 29.9	99 – 210
GL-5	Extreme-pressure (EP)	Mineral or semi-synthetic or synthetic	10.7 – 26.5	90 – 194
GL-5(LS)	Extreme-pressure (EP) + friction modifiers (FM)	Mineral or synthetic	10.7 – 15.3	100 – 149

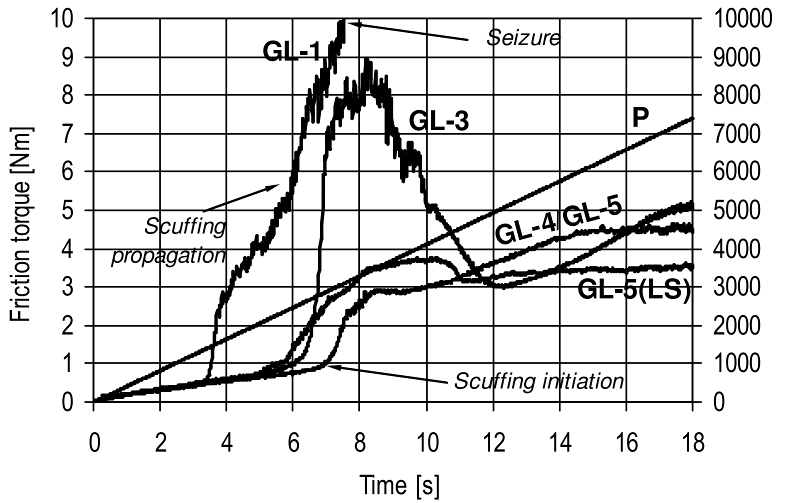

Fig. 2. Qualitative discrimination between the gear oils of various API GL performance levels

Rys. 2. Jakościowe różnicowanie samochodowych olejów przekładniowych pod względem klasy jakościowej API GL

From **Fig. 2**, it is apparent that the API GL-1 gear oils, without lubricating additives, promote rapid scuffing initiation at a low load (approx. 1500 N), then the rapid increase in the friction torque, leading to immediate seizure, which is also at a low load (approx. 3200 N).

A different behaviour was observed for most of the tested API GL-3 gear oils. The difference between the friction torque curves obtained for the API GL-1 oils and the GL-3 gear oils is that the latter delay scuffing initiation (it occurs at the load of approx. 2600 N). In comparison with the API GL-1 gear oils, GL-3 oils, in the most cases, prevent seizure during the entire run, since the load reaches its maximum possible value, i.e. 7400 N. This results from application of the antiwear (AW) package of lubricating additives in GL-3 oils, mitigating the scuffing propagation. More information on the behaviour of the API GL-3 oils can be found in the mentioned work **[L. 6]** and monograph **[L. 7]**.

Gear oils of the highest API GL performance levels, i.e. API GL-4, GL-4/GL-5, and GL-5 (in **Fig. 2** all denoted as GL-4/GL-5), contain the most effective package of extreme-pressure (EP) lubricating additives. Therefore, they exhibit completely different curves of the friction torque. They show a rather mild rise in the friction torque after the scuffing initiation, then the friction torque quickly stabilises with a constant but not intensive rise until the end of the run. All of these oils prevent seizure.

Although quite similar to the GL-4/GL-5 gear oils, the API GL-5(LS) oils generally give the mildest character of the scuffing propagation in the last phase of the experiments (from the 12th to the 18th second). Gear oils of this level contain, apart from EP additives, special lubricating additives (friction modifiers – FM), preventing the occurrence of the stick-slip phenomenon, which can be attributed to the described behaviour.

To sum up this part of the experiment, various, distinct shapes of the friction torque curves have been identified for automotive transmission and axle oils of the API GL-1 performance level (without lubricating additives), GL-3 (with AW additives), a group of oils of GL-4, GL-4/GL-5, GL-5 performance levels (with EP additives), as well as GL-5(LS) oils (with EP and FM additives). Thus, the results obtained make it possible to preliminarily check whether the tested gear oil fulfils the respective API GL service requirements in a way that may be called the qualitative discrimination.

In spite of the above, gear oil manufacturers seek tests that will allow them to assess oils both in a qualitative and quantitative way based on numerical values. In the new test, the limiting pressure of seizure p_{oz} is calculated to assess the oils quantitatively.

Quantitative discrimination

The ranges between minimum and maximum values of the limiting pressure of seizure p_{oz} obtained for the tested groups of the gear oils are presented in **Fig. 3**. Each point represents one oil. The assessed uncertainties of measurement are also shown in the figure below the minimum value and over the maximum one in each group. The oils for which the minimum and maximum value of p_{oz} was obtained are denoted symbolically, where the first segment represents the type of the base oil (M – mineral, S – synthetic), and the second one denotes ν_{100} [L. mm^2/s], and the third one – VI (**Tab. 1**).

From **Fig. 3**, it is apparent that the values of the limiting pressure of seizure p_{oz} make it possible to discriminate between the oils of the API GL-1, GL-3 and the oils of the higher performance levels. However, the GL-1 and GL-3 oils cannot be discriminated, because the uncertainties of measurement overlap each other. The API GL-4, GL-4/GL-5, GL-5, and GL-5(LS) oils cannot be discriminated either; although, it can be observed that the higher GL number, the higher maximum p_{oz} value for GL-4, GL-4/GL-5, and GL-5 gear oils.

Neither the kinematic viscosity, nor the viscosity index, exert any effect on the limiting pressure of seizure p_{oz}. It can probably be attributed to very severe conditions in the friction zone, under which rheological properties of lubricants do not play any role.

It can also be seen that the API GL-1 oils, without lubricating additives, give the p_{oz} values in the lowest range. AW additives in GL-3 oils give the p_{oz}

values in the medium range. GL-4, GL-4/GL-5, GL-5, and GL-5(LS) oils, all with very effective EP additives, give the highest p_{oz} values. However, FM additives in GL-5(LS) gear oils do not affect (increase) p_{oz}.

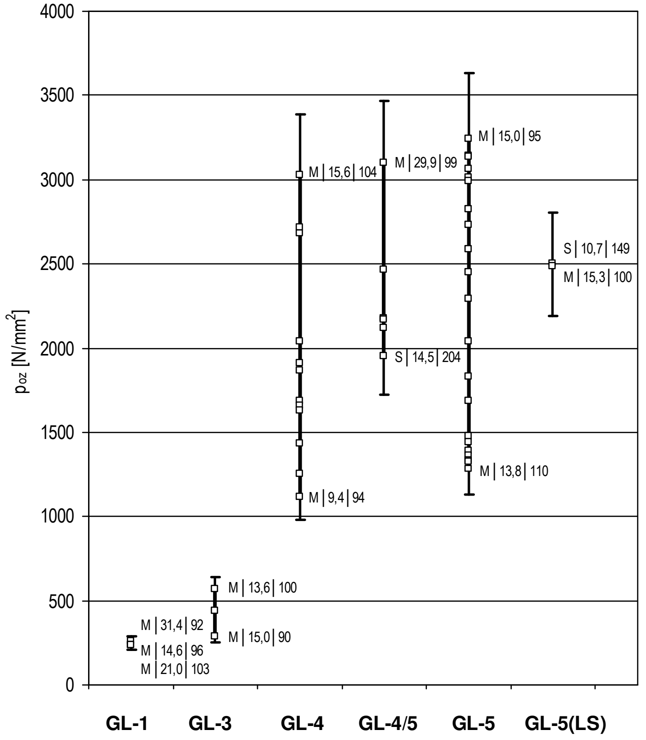

Fig. 3. Quantitative discrimination between the gear oils of various API GL performance levels

Rys. 3. Ilościowe różnicowanie samochodowych olejów przekładniowych pod względem klasy jakościowej API GL

Wear scar microanalyses

As a result of chemical interaction between the active lubricating additives in the oil and the steel surface, there is the formation of inorganic compounds of iron with sulphur, phosphorus, zinc, and oxygen, depending on the type of the lubricating additive in gear oils. The AW additives (based on zinc dithiophosphates, e.g. ZDDP) form polyphosphate structures **[L. 8]**, while the EP additives (based on organic S-P compounds) form, e.g., iron sulphide FeS **[L. 9]**. The thick layer of polyphosphates prevents the direct contact of the surface asperities. FeS compounds, apart from hampering the creation of adhesive bonds, facilitate the shearing of the chemically modified surface asperities, reducing the wear intensity.

Thus, to interpret the tribological results, the worn surface was analysed using a scanning electron microscope (SEM) and energy dispersive spectrometer (EDS). The analyses were carried for those oils that gave, in the particular groups of the API GL performance levels, the extreme values of the limiting pressure of seizure p_{oz}. For reference, the results for one of the GL-1 oils are also presented. The results of quantitative EDS microanalyses of the sulphur concentration in the wear scar surface layer are provided in **Fig. 4** The EDS microanalyses were carried out at 3 different points (micro-areas) of the wear scar. The lower graph shows the average values of the sulphur.

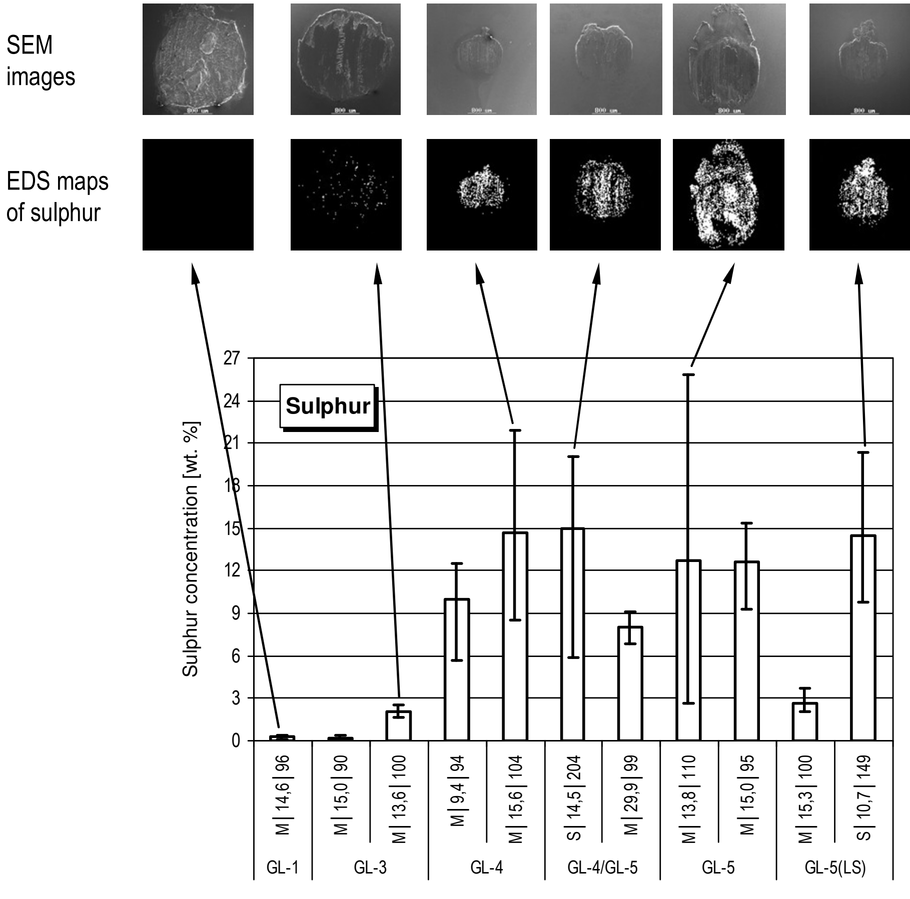

Fig. 4. Quantitative EDS microanalyses of the sulphur concentration in the wear scar surface layer for the selected gear oils, together with SEM images of the wear scars and EDS maps of the sulphur distribution

Rys. 4. Zawartość siarki w warstwie wierzchniej śladu zużycia dla wybranych olejów oraz obrazy skaningowe (SEM) śladów zużycia i mapy EDS rozkładu siarki concentration and the ranges between the lowest and highest its concentration at different points of the wear scar. The figure also shows, for the highest sulphur concentrations, SEM images of the wear scars together with EDS maps of sulphur distribution on the entire wear scar surface layer. To facilitate the analysis, the scale of all images is the same.

As indicated by **Fig. 3**, the API GL-1 oils, without lubricating additives, give the p_{oz} values in the lowest range. This is a result of the lack of lubricating additives in such oils. In **Fig. 4**, the concentration of sulphur in the wear scar surface layer is the lowest and comes from natural contamination of crude oil with this element. The lack of the protective layer on the friction surface leads inevitably to seizure (**Fig. 2**). The SEM image shows a very destroyed wear scar for the GL-1 oil due to seizure.

The API GL-3 oils give the p_{oz} values in the medium range (**Fig. 3**). They contain a package of AW additives that are not so chemically effective under scuffing conditions, which gives very weak signals from sulphur – **Fig. 4**. The GL-3 oil, denoted as M┃13,6┃100, gives a higher concentration of sulphur than the oil denoted as M┃15,0┃90, which correlates with the higher p_{oz} value (**Fig. 3**). For the former, the protective action of sulphur compounds smoothes the wear scar surface in comparison with the GL-1 oil (SEM images in **Fig. 4**), and, in most cases, it prevents the tribosystem from seizure (**Fig. 2**).

The API GL-4, GL-4/GL-5, GL-5, and GL-5(LS) oils, give the highest p_{oz} values (**Fig. 3**). All of them contain a very effective package of EP additives, "leaving" much more sulphur in the wear scar surface layer than GL-3 oils (**Fig. 4**). This smoothes the wear scar surface and, in all the cases, prevents the tribosystem from seizure (**Fig. 2**).

CONCLUSIONS

By using the new four-ball scuffing test, it is possible to discriminate between the API GL performance levels of automotive transmission and axle oils in a qualitative way – various, distinct shapes of the friction torque curves were identified for the gear oils containing various lubricating additives, i.e. API GL-1, GL-3, a group of GL-4/5 oils, and GL-5(LS) oils.

It is also recommended to apply the values of the limiting pressure of seizure (p_{oz}), being the result of the new test, which makes it possible to discriminate among the API GL-1, GL-3 and the other gear oils in a quantitative way; although, the quantitative way has a lower resolution than the qualitative one.

Thus, unlike other known and widely used scuffing tests (standardised four-ball and gear tests), the proposed approach can enable R&D laboratories devoted to certifying automotive transmission and axle oils to significantly reduce the duration and costs of the tribological tests of the EP properties of gear oils.

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Streszczenie

Dokonano oceny możliwości zastosowania własnej metody, nazwanej *metodą wyznaczania granicznego nacisku zatarcia* p_{oz}, do różnicowania samochodowych olejów przekładniowych pod względem klas jakościowych API z punktu widzenia właściwości przeciwzatarciowych. Badania tą metodą

wykonywane są w warunkach zacierania czterokulowego węzła tarcia, zainicjowanego liniowo rosnącym obciążeniem, aż do wystąpienia zatarcia. W licznych publikacjach dowiedziono, że nowa metoda badawcza wykazuje wiele zalet w porównaniu ze znormalizowanymi metodami badań właściwości przeciwzatarciowych środków smarowych – badania nową metodą pozwalają uzyskać lepszą zdolność rozdzielczą, a do tego są szybsze, tańsze i ich precyzja jest porównywalna z precyzją znormalizowanych badań właściwości przeciwzatarciowych środków smarowych.

Zbadano reprezentatywną grupę samochodowych olejów przekładniowych klasy jakościowej od API GL-1 do GL-5(LS), wykorzystując aparat czterokulowy ze ślizgowym węzłem tarcia. Wykazano, że metoda wyznaczania granicznego nacisku zatarcia p_{oz} pozwala, w sposób jakościowy (na podstawie analizy przebiegu momentu tarcia) i ilościowy (na podstawie uzyskanych wartości wskaźnika p_{oz}), różnicować samochodowe oleje przekładniowe pod względem klas jakościowych API, chociaż sposób jakościowy jest bardziej efektywny (lepsza zdolność rozdzielcza) w porównaniu ze sposobem ilościowym.

Ponieważ nowa metoda badawcza pozwala na redukcję kosztów badań (wykorzystuje się tu proste, tanie próbki testowe) oraz ich czasochłonności, może być efektywnie wykorzystana w przemysłowych laboratoriach badawczo-rozwojowych w celu weryfikacji jakości samochodowych olejów przekładniowych.