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THE RELATIONSHIP BETWEEN THE LUBRICATING PROPERTIES INDICATORS OF GEAR OILS DETERMINED BY DIFFERENT METHODS

ZALEŻNOŚĆ MIĘDZY RÓŻNYMI WSKAŹNIKAMI WŁAŚCIWOŚCI SMARNYCH SAMOCHODOWYCH OLEJÓW PRZEKŁADNIOWYCH

Key words:

wear indicators, gear oils, lubricated properties, four ball apparatus, crossed-cylinder tester

Słowa kluczowe:

wskaźniki zużycia, oleje przekładniowe, właściwości smarne, aparat czterokulowy, tester ze skrzyżowanymi walcami

Summary

The research presented in this article analyses the relationship between the different indicators characterizing lubricating properties of gear oils. The values of the analysed indicators were determined with the use of different methods

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and tribotesters. A four-ball apparatus and a crossed-cylinder wear tester were employed. Several dozen oils were tested, and various measurements of their lubricating properties have been determined. The research results indicate the possibility of describing the relationship between the indicators with the use of a mathematical model. The artificial neural model was developed that presents the relationship of load-wear index and Brugger pressure. The discussion of the model quality is presented and the ability to generalize of the neural model is demonstrated.

INTRODUCTION

Experimental research in tribology is based on finding solutions to application problems and to improve tribological knowledge. The complexity of the issues concerning friction and wear causes the differentiation of methods and indicators for assessing the tribological properties in various situations of friction. That fosters the development of tribological testers. Many methods and testers to evaluate the tribological properties have resulted in an increase in experimental data, and this new data differs significantly. However, suitable control of test condition and design criteria may improve the tests reliability **[L. 1, 2].**

The wear test configuration depends on the purpose of the study. The main reason for these tests is the simulation of wear processes that produce data useful in practice. The ability to predict the wear of materials and lubricating properties is crucial for solutions to application problems. However, tribo-simulation test results should never be used to calculate the lifetime of a part in practice, due to the fact that single values cannot give a universal description of a tribosystem **[L. 3]**. Simulation tests data are helpful mainly in the preselecting of materials and lubricants for the special friction applications, and they also provide important information for the prediction and explanation of phenomena associated with friction and wear. In order to increase the use of data from tribological tests, research is conducted on the methods which attempt to generalise the experimental results **[L. 4]**.

In tribological practice, different methods are used for the assessment of results concerning the same kinds of wear. It is important to identify the correlation between the results obtained and to assess the effectiveness of the methods used to determine the friction and wear characteristics. The comparison of different tests used for the evaluation of the galling resistance was presented **[L. 5]** and their ability to assess the galling tendencies of tool steel was evaluated. The comparison of the wear test results with the use of the four-ball tester and the pin-on-disc machine, conducted in the boundary lubricating regime, indicated a good correlation **[L. 6]**. The research results of the two method used for differentiation between the API GL performance levels of automotive gear oils were compared **[L. 7]**. Two different tribotesters were used: a crossed-cylinder tester and the four-ball tester that is commonly used in the evaluation of oils. A recent paper demonstrates that crossed-cylinder geometry can be used for different tribological testing **[L. 8–11]**. The research results indicate that both selected measurements make it possible to differentiate between oils. However, the proposed test method performed in the crossed-cylinder wear tester show a better relevance to the differentiation of oil performance levels. Additionally, the crossed-cylinder wear test is relatively quick and tester is inexpensive. The opportunity to determine the effectiveness of lubricants in the process of friction with the use of the relatively inexpensive tests is an important issue with regard to improving the effectiveness of the tribological research.

The aim of the presented investigation was the identification of the relationship between the lubricated properties of oils that determined with the use of crossed-cylinder tester and four-ball tester, based on the experimental data.

EXPERIMENTAL DETAILS

Two different processes of lubricated friction were conducted with the use of the commercial oils used for the automotive gears. The research included various mineral, synthetic, and semi-synthetic oils of GL-1, GL-3, GL-4, and GL-5 performance levels according to API. Using the four-ball **(Fig. 1)** and crossed-cylinder testers **(Fig. 2)** the wear characteristics were determined.

Fig. 1. Four-ball apparatus
Rys. 1. Aparat czterokulowy

The four-ball apparatus was used for the determination of anti-wear and anti-seizure properties of oils, namely, an average wear scar diameter (d), load-wear index (Ih), weld point (Pz), and non-seizure load (Pn). The friction process parameters are given in **Tab. 1.**

Table 1. Parameters of the four-ball test
Tabela 1. Parametry procesów tarcia na aparacie czterokulowym

Parameter	Unit	Value
rotation velocity	rot/min	1450
initial load	N	785
step-wise increasing load	daN	78.5 - 785
time of the each ran	s	10

The anti-wear properties of lubricants, investigated with the use of crossed-cylinder tester, have been determined using the ellipse-shaped wear scar produced by a rotating roller onto the fixed cylinder in the tests under the condition shown in **Tab. 2**. The “Brugger pressure” (B) was calculated as the ratio of the applied load and the area of the wear scar. In each test, the wear scar axes [longer (a) and shorter (b) of the ellipse] were measured using an optical microscope with an accuracy of 0.01 mm.

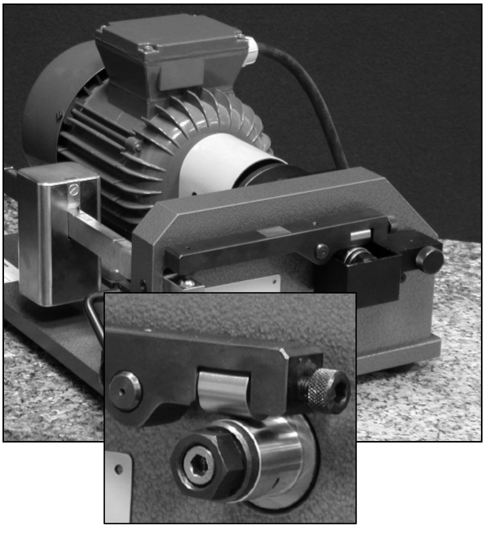

Fig. 2. Crossed-cylinder tester
Rys. 2. Tester ze skrzyżowanymi walcami

Table 2. Parameters of the crossed-cylinders test
Tabela 2. Parametry procesów tarcia na testerze ze skrzyżowanymi walcami

Parameter	Unit	Value
rotation velocity	rot/min	960
load	N	400
time	S	30

The balls used in the four-ball test and the cylinders used in crossed-cylinders test were made of AISI 52100 steel. Before each test, the samples were cleaned with petrol.

RESULTS AND MODELLING

In the research results, the wear characteristics of the friction contact steel-steel and lubricated with the use of different oils were determined. The characteristics for the oils were examples from different groups (mineral, semi-synthetic and synthetic) and are presented in **Figs. 3–5**. The tribological characteristic: load-wear index (Ih), that were determined using the four-ball tester were presented in **Fig. 3.** The wear characteristic, "Brugger pressure" (B), was determined using a crossed-cylinder tester and is presented in **Fig. 4**.

The research results indicate that the indexes, determined using crossed-cylinder tester, differ and are related to the oil type. Significantly higher values of the wear axis were obtained for the mineral oils than for the synthetic oils, despite the same performance levels according to API. The average longer axes of wear scare for the mineral oils GL-5 was 2.63 mm, while the average longer axes for the synthetic oils was 1.54. The average longer axis of the wear scare

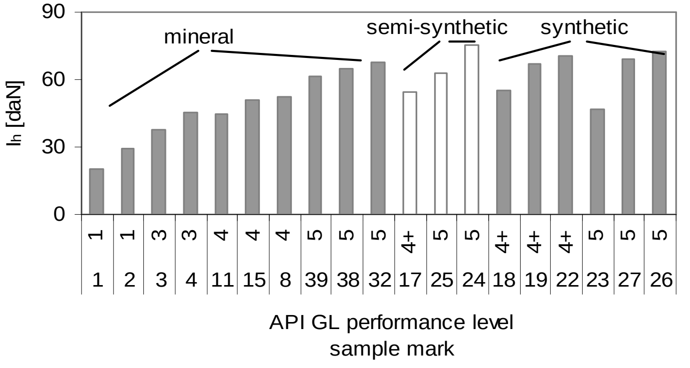

Fig. 3. The examples of the determined load-wear index for gear oils
Rys. 3. Przykłady wyznaczonych wartości wskaźnika zużycia pod obciążeniem dla olejów przekładniowych

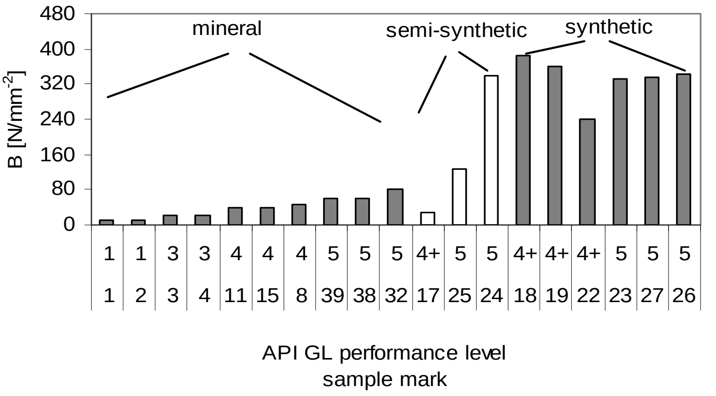

Fig. 4. The examples of the determined "Brugger pressure" for gear oils
Rys. 4. Przykłady wyznaczonych wartości obciążalności oleju dla olejów przekładniowych

for the mineral oils of GL-5 was 2.63 mm while the average longer axes for the synthetic oils was 1.54 mm. A smaller differences for different kinds of oils of the same performance levels were obtained for the wear index Ih determined with the use of the four-ball tester. The average value for the mineral oils, Gl-5, was 61.7 daN, while for synthetic oil it was 69.9 daN.

Both of presented test methods were used for the different wear indicators for the determination of the same material pairs. One of the main aims of the presented study was the identification of the relationship between wear indicators determined by different methods. Therefore, the analysis of research results were conducted in order to determine the type of relationship.

The experimental data was used to carry out the modelling process of the selected wear characteristics for gear oils, which included the load-wear index and "Brugger pressure".

Both indicators characterized the anti-wear properties of oil and an increase in their value indicates an improvement in the lubricating properties of the oil. Therefore, the existence of a positive correlation between the investigated indicators was assumed.

Experimental results show the impact of the type of oil in a relationship between the wear indicators; therefore, the qualitative variable, namely the type of oil, was included in the model. The multilayer perceptron MLP was the best architecture of a neural model for the analysed object. The developed model MLP(4,4,1) had two input variables. One of them was qualitative of the three values (mineral, semisynthetic and synthetic) and characterized the type of oil, and the second one was quantitative and presented the value of B indicator. The I_h wear indicator was the model output. The model had four neurons in a hidden layer.

As a result the analysis of the regression statistics, a good correlation of model calculations with the experimental data was found. However, the analyses showed an I_h decrease, while a B increase was shown for synthetic oils. Such incompatible with the assumptions, a trend of the experimental data, probably results from very small and similar values of wear diameters obtained from the use of the crossed-cylinder tester in the friction process of synthetic oils.

The I_h decrease with the B increase is substantively unreasonable, so it was impossible to verify positively the model developed.

In the next step of modelling the data for synthetic oils were ignored. The multilayer perceptron MLP (1,4,1) was developed that has one input (B) and output (I_h) and four neurons in a hidden layer. The high values of correlation coefficients were achieved for three of data vectors: training, verification and test **(Tab. 3).**

Table 3. The regression characteristics of MLP (1,4,1)
Tabela 3. Charakterystyki regresyjne modelu MLP (1,4,1)

	Training	Verification	Test
Data Mean	55.25	56.73	56.90
Data S.D.	13.51	11.68	7.85
Error Mean	0.55	-2.88	-0.24
Error S.D.	4.97	6.19	3.45
Abs E. Mean	4.04	5.22	2.30
S.D. Ratio	0.37	0.53	0.44
Correlation	0.93	0.85	0.94

As is apparent from the characteristics of the regression **(Table 3)**, an excellent correlation was achieved for the test data that were not taken into account in the development of the model. This demonstrates the model's ability to generalise the results and positively verifies the neural model.

The experimental data and values calculated by the MLP model, for investigated mineral and semi-synthetic oils, are presented in **Fig. 5.**

After the artificial neural model was developed, it was used for the calculation of the values of the load-wear index for the synthetic gear oils. The results are presented in **Fig. 6.**

Analysis of the data presented in **Figure 6** shows that the values for the points marked in the figure as 1 (s5), 2 (s5), 3 (s4 +) and 4 (s4 +) were probably not exactly measured. Points 1 (s5) and 2 (s5) represent values of wear for oils

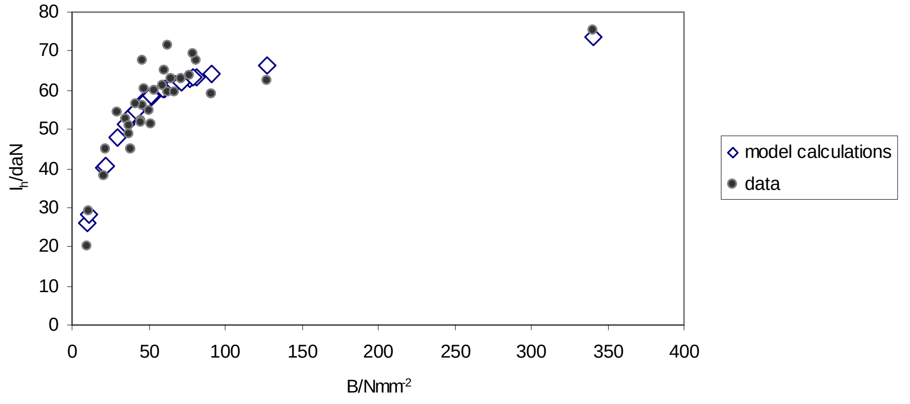

Fig. 5. The relationship between I_h and B for investigated mineral and semi-synthetic gear oils, data and values calculated by models

Rys. 5. Zależność między I_h a B dla przekładniowych olejów mineralnych i półsyntetycznych, dane eksperymentalne i wyliczenia modelu

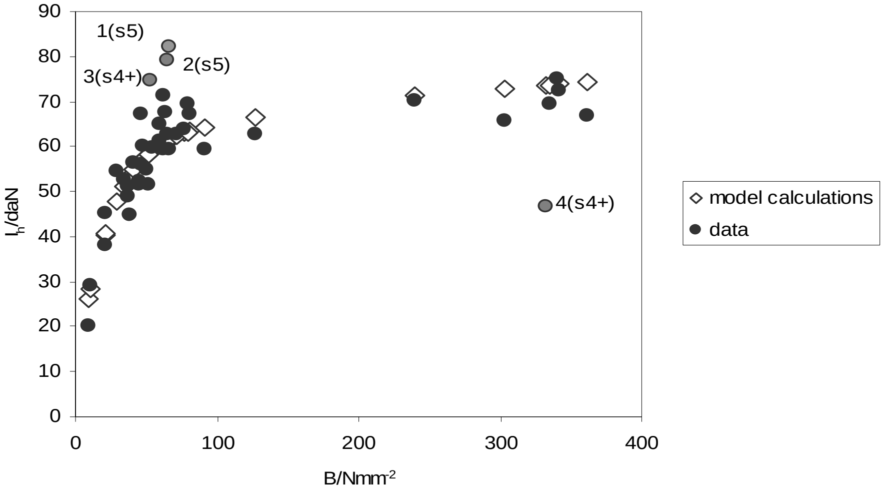

Fig. 6. The relationship between I_h and B for investigated gear oils, data and values calculated by models for all investigated oils

Rys. 6. Zależność między I_h a B dla wszystkich zbadanych przekładniowych olejów, dane eksperymentalne i wyliczenia modelu

from the group of synthetic oils, GL-5, for which the values of B were above 300 [N/mm^2], while the experiments results were, in both cases, only about 64 [N/mm^2]. A similar situation occurred in the case of point marked 3(s4+), which represents the synthetic oil of a group GL-4 +, for which the "Brugger pressure" values were comparable with oils of group GL-5. For the point marked 4 (S4 +), belonging to the group of synthetic oils GL-4 +, too low of a value of I_h (55 [daN]) was measured, and the average value for this group was 67[daN].

The analysis shows that the developed neural model predicts values of I_h indicator based on the B indicator value for all of tested oils well. The determination coefficient of experimental data and calculated by the model was $R^2 = 0.85$.

CONCLUSIONS

It was shown that the possibility of the relations identified between the different indicators of wear that were determined using different methods.

In the research result, the relationship was identified between the load-wear index, determined using four-ball tester, and the wear indicator, determined using crossed-cylinder tester, for gear oils. The relation between indicators were formalized using a neural network, and the multilayer perceptron was developed that allows the prediction of the load-wear index on the basis of "Brugger pressure”. The model characterized by a good quality of a high determination coefficient, and has the possibility to generalize the conclusions. The research and analysis was carried out on the example of the wear indicators of gear oils. However, the identification of the indicators’ relationship may be of the general importance. In the case of tribological tests and the generalization of results, this is particularly significant.

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Streszczenie

W ramach badań prezentowanych w artykule dokonano analizy zależności pomiędzy wskaźnikami zużycia charakteryzującymi właściwości smarne olejów. Wskaźniki wyznaczono dla samochodowych olejów przekładniowych dzięki zastosowaniu różnych metod. W badaniach wykorzystano aparat czterokulowy i tribotester ze skrzyżowanymi walcami. Przetestowano kilkadziesiąt olejów, dla których wyznaczono różne wskaźniki charakteryzujące właściwości smarne. W rezultacie przeprowadzonych analiz wykazano możliwość opisania zależności między wskaźnikami za pomocą modeli matematycznych. Opracowano model logarytmiczny oraz z zastosowaniem sztucznych sieci neuronowych. Modele przedstawiają zależności wskaźnika zużycia pod obciążeniem i wskaźnika „Brugger preasure” wyznaczanego z użyciem crossed-cylinder tester. Przeprowadzono dyskusję jakości modeli, wykazano zdolność modelu neuronowego do generalizacji.