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EVALUATION OF LUBRICATION EFFICIENCY BASED ON WEAR DURING VARIABLE LOADS AND SLIDING VELOCITIES

OCENA EFEKTYWNOŚCI SMAROWANIA NA PODSTAWIE ZUŻYCIA PRZY ZMIENNYM OBCIĄŻENIU I PRĘDKOŚCI POŚLIZGU

Key words:

Greases, lubrication efficiency

Słowa kluczowe:

smary plastyczne, efektywność smarowania

Abstract

The results of the tribological studies on the lubrication efficiency of greases evaluated based on tribological tests performed at varying pressure p and rubbing speed v are presented. For the efficiency criterion, the volume of wear $V_{F(d)}$ obtained from the regression equations of wear was adopted (wear F (d) = f (F, v)). Six different lubricants were tested; two of them were commercial greases, and four of them were compositions based on them,

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including conventional solid greases (PTFE, tin, copper, and boron nitride). The experiment was carried out on a four-ball extreme pressure tester according to a rotatable design on five levels. For each of the selected lubricants, a regression function was developed that defined wear as a function of rubbing speed and load. The volume of the obtained wear $V_{F(d)}$ was calculated and relevant conclusions were drawn.

INTRODUCTION

Plastic greases, along with lubricating oils, make the primary means to reduce friction and wear in tribological systems. Tribological tests and theoretical considerations have designated areas of the application of greases in the construction of machines and mechanisms. It can be generally concluded that greases are complementary lubricating oils in the sense that they are used everywhere where oil lubrication is difficult, unstable, or uneconomical. Due to the limited possibilities of removing the friction heat generated by greases, they are used primarily in systems with low and medium speeds of components of tribological systems. Conversely, because of the ability of greases to create a stable boundary layer and a thickness from 1.2 to 3.5 times bigger than the thickness formed by a base oil **[L. 1, 2],** they are suitable mainly for the lubrication of the sliding pairs working in a mixed friction area.

The contact of the surface during friction is always discrete due to its roughness. According to **[L. 3, 4**], in the contact of the surface, three areas can be distinguished, namely, the polymolecular boundary layer area, the mono - or bilayer film area, the areas of the direct contact of inaccuracy, and at interchange - their deformation or destruction. By adopting such a model of the surface contact, the friction force between them may be expressed as follows:

$$F_T = \alpha A \sigma_p + \beta A \sigma_m + \gamma A \sigma_s, \tag{1}$$

where

A – contact surface (total),

α, β – share of the contact surface respectively with the polymolecular and monomolecular layer of grease,

γ – share of the contact surface not covered with a grease layer (metal contact),

σ_p, σ_m, σ_s – shear strength, respectively the poly-molecular and monomolecular layer of grease and native metals.

Therefore, a good grease is one where a wide area of external extortion (p, v) provides a sliding pair fulfilling the condition $\alpha \approx 1$ or $\alpha + \beta \approx 1$. The wider the range of loads and rubbing speeds at which the grease fulfils this condition, the more efficient it is. The limit of the area of the extortion *(p, v)* is determined mainly by the heat at the contact surface, which causes the heating of the thin films of the sliding materials and of the grease separating them. When exceeding a certain critical temperature, proper for a given grease and the associated materials, an imbalance of the metastable state occurs, and the boundary layers are either destroyed or created **[L. 5, 6]**. It should be emphasized that the heat is one of the most important factors affecting the tribological characteristics of sliding nodes operating in the area of mixed friction. Whereas, other phenomena, e.g., the catalytic activity of a pure metallic surface, a phenomenon of exoelectrons (Kramer effect) or mechanical stress, always favour the formation of boundary layers **[L. 7, 8]**.

Analysis of the literature concerning grease lubrication efficiency shows that the conclusions of the study of those issues are, with very few exceptions, drawn from the results of experiments conducted at constant values of pressure and rubbing speed or at only one variable parameter, i.e. pressure or rubbing speed. An attempt at generalization concerning the results of such studies may be subject to a significant error, because the effectiveness of a grease in the sliding nodes operating at mixed friction is determined predominantly by the temperature on the contact surface. It is proportional to the product of p and v, i.e. pressure and rubbing speed. Any change in load or rubbing speed involves a change in the amount of heat generated during the friction and that in turn changes the reaction ability of the additive or the stability of the boundary layer, which affects the quantity friction and wear. Therefore, the evaluation of the lubricating ability of a tested lubricant (composition) made based on tests conducted for fixed values of p, and v or only one variable factor, e.g., pressure, will always be inaccurate and vitiated by error. This error in estimating the lubricating ability of the tested grease will be limited to a minimum, while at its assessment, a wide range of extortion will be taken into account. The larger the scope of the (p, v), the more accurate is the assessment of the grease's lubrication efficiency. The rational solution to this particular problem is possible if the research is carried out using the methods of a planned experiment for two input variables, i.e. pressure (p) and rubbing speed (v). Then, the expenses will be smallest, and the time required for finding the regression function (a mathematical model of the research object) will be the shortest. At the same time, the received wear regression functions will enable the conducting of the optimization process in accordance with the adopted criterion.

In the Department of Machine Design and Tribology of the Wroclaw University of Science and Technology, a tribological study of six greases was conducted in terms of their efficiency in the lubrication of steel sliding pairs working in the mixed friction conditions but evaluated based on their wear characteristics obtained at variable pressures and rubbing speeds.

METHOD AND TEST CONDITIONS

The research was carried out using a four-ball extreme pressure tester made by the Institute for Technology in Radom. The tests were conducted according to a rotatable design for five levels. In the research, two independent quantities were adopted as variables (input quantities), i.e. given load F, rubbing speed v and sliding material hardness H. The output quantity (criterial) was wear d measured by the ball wear scar diameter over the friction distance. This wear was measured along sliding path s =33.5 m. The latter corresponds to the friction distance of the rotating ball during the standard (PN-76/C-04147) determination of limit wear load index G_{oz}. As a result, values of the limit wear load index G_{oz} calculated based on the research conducted according to the experiment's plan can be compared with the values of G_{oz} obtained from the tests performed according to the obligatory standard. Ranges of the input quantities were determined by applying the criterion that each investigated object must properly function for all the sets of input quantities and must not seize up **[L. 9, 10]**. Having satisfied the above criterion and taken the four-ball tester's potential into account, after the preliminary tests, the following intervals were adopted for the particular variables:

- Load F= 32–128 daN, corresponding to average Hertz pressure p_H of 2165–3437 MPa; and,
- Rubbing speed *v*–0.04–0.68 m/s (corresponding to the top ball's rotational speed of *n*–104–1772 rpm).

Since three input quantities (S=2) were adopted, the basic experiment design data was as follows:

- Star arm a = 1.414,
- Number of experiments at the central point N_o = 5, and
- Total number of experiments N = 13.

The relationship between the numerical values of the standardized variables and those of the natural variables is shown in **Table 1**.

Table 1. Values of the standardized and natural input variables at different levels of the experiment

Tabela 1. Wartości zmiennych wejściowych standaryzowanych i naturalnych na poszczególnych poziomach eksperymentu

Variable	Standardized values / Natural variables	-1.414	-1	0	1	1.414
x_1	Load F [daN]	32	46.06	80	113.9	128
x_2	Rubbing speed v [m/s]	0.04	0.133	0.36	0.586	0.68

The input quantities were correlated with the output quantities (measured during the experiment) by mathematical relations. Regression analysis was used for that purpose. A second order polynomial was adopted as a function approximating the test results. For the two input variables, the polynomial has the following form:

$$\acute{y} = b_0 + b_1 x_1 + b_2 x_2 + b_{11} x_1^2 + b_{22} x_2^2 + b_{12} x_1 x_2 \qquad (2)$$

where

$b_0, b_1, ...,b_{22}$ - the regression function coefficient,

x_1, x_2 - the input quantities (respectively F, v),

$\acute{y}$ – the model output quantity (bearing ball wear scar diameter d).

Approximation of the measurements with the above-mentioned polynomial was done by a minimum sum of squared errors. In order to determine the relationship between the measured experimental quantities y and model input quantities x, multidimensional correlation coefficient R was calculated in accordance with **[L.11].** In order to obtain the most reliable relation, the significance of the multidimensional correlation coefficient and that of the regression function were tested using the F-Snedecor test based on the analysis of regression equation variance **[L.11].**

Based on the regression equations of the balls wear obtained in the presence of the analysed greases, the quantitative effectiveness of the investigated greases was conducted according to the criterion of its wear. That evaluation of the effectiveness was carried out using a method of minimal volume of wear described in **[L. 12].** According to that method, the function of wear is the regression equation of wear d = f(F,v), which can be written as F(d) = f(F,v). A graphic image of that function is a surface formed by the values of wear d measured in experiments in which extortions F and v assume the values resulting from the adopted plan of the experiment. The volume of the solid under the surface is a measure of wear, which was called the volume of wear $V_{F(d)}$ and calculated from the following:

$$V_{F(d)} = \int_{v_0}^{v_1}\int_{F_0}^{F_1} f(F,v)\cdot dF\cdot dv \qquad (3)$$

where

v_0 , v_1 , F_0 , F_1 – limited (minimum and maximum) rubbing speed values v and load F,

$f(F,v)$ – wear function $F(d)$, i.e. the regression equation of wear for the analysed grease.

The double integral (3) was solved numerically using the SURFER program designed for plotting and analysis of three-dimensional surfaces **[L. 13].** The program enables the solving of the integral by three methods, namely by the trapezoidal, Simpson, and Simpson 3/8 method. The calculations were carried out by each of the three methods. Since the limits of extortion in the tests (carried out using the rules of the planned experiment) are constant, the calculated values can be compared. The smaller the value of the calculated volume $V_{F(d)}$, the better are the lubricating properties of a grease, because the wear of the lubricated surfaces in the studied area of extortion (F, v) is smaller.

MATERIALS AND THEIR DESCRIPTION

The following materials were used in the tests:

1. Bearing balls 12.7 mm in diameter made of bearing steel 100Cr6 in accuracy class 16 and dimensional group S = 0_m. Further characteristics of the balls met PN-83/M.-86452 standard.
2. Two commercial grease types for the lubrication of sliding nodes and rolling bearings, i.e.
   - 1S car grease, for the lubrication of joints and other sliding nodes in automobiles, and
   - Litomos EP-25 – molybdenum grease of the domestic production. It contains the EP additive, a corrosion inhibitor and 4-5% of molybdenum disulphide. It is designed for lubrication of constant velocity joints, ball joints, pull rods, bolts, connectors, slide, and rolling bearings.
3. Four of our own compositions, obtained by modifying the 1S grease by six per cent of the powder of one of the following solid lubricants: PTFE, copper, tin, or boron nitride.

Polytetrafluoroethylene (PTFE) is a suspension of Tarflen of 20 to 40 μm granulation manufactured by Nitrogen Plant in Tarnow. Similar granulation was featured by the powder of tin and copper. Boron nitride was of 10 μm grain size.

TEST RESULTS AND DISCUSSION

From the test results, the following regression functions for the investigated greases were derived:

- Automotive grease 1S
  $d = 2.076241 - 0.041076\,F - 5.971706\,v + 0.000273\,F^2 + 6.434437\,v^2 + 0.042169\,Fv$,
- Litomos EP-25 grease
  $d = 0.673277 - 0.006701\,F - 0.944468\,v + 0.000044\,F^2 + 0.934495\,v^2 + 0.008587\,Fv$,
- 1S grease fulfilled in 6% of PTFE

$$d = 0.561542 - 0.005488\ F - 0.878001\ v + 0.000044\ F^2 + 0.866278\ v^2 + 0.007874\ Fv,$$

- 1S grease fulfilled in 6% of tin

$$d = 2.083131 - 0.038723\ F - 5.610007\ v + 0.000222\ F^2 + 4.590807\ v^2 + 0.050597\ Fv,$$

- 1S grease fulfilled in 6% of cooper

$$d = 1.894227 - 0.030594\ F - 5.108929\ v + 0.000149\ F^2 + 3.462415\ v^2 + 0.04977\ Fv,$$

- 1S grease fulfilled in 6% of boron nitride

$$d = 2.36212 - 0.045793\ F - 7.044118\ v + 0.000258\ F^2 + 6.35321\ v^2 + 0.060463\ Fv.$$

Table 2 shows the values of the multidimensional correlation coefficients R and of the F-Snedecor test coefficients calculated for those equations. High R-values indicate a close relation between the wear values measured during the experiment and the ones obtained from the equations presented above. In addition, the calculated values of coefficient F are much higher than the critical value of the test.

Table 2. Values of the multidimensional correlation R coefficients and of the F-Snedecor test coefficients

Tabela 2. Wartości współczynników korelacji R i testu F-Snedecora

Regression equation for:	Coefficient of multidimensional correlation R	Coefficient of the F-Snedcor test	
		F	F_{kr}
car grease 1S	0.97539	19.56	4.28
1S grease fulfilled in 6% of tin	0.98869	43.45	4.28
1S grease fulfilled in 6% of boron nitride	0.97958	24.56	4.28
1S grease fulfilled in 6% of cooper	0.98252	27.85	4.28
1S grease fulfilled in 6% of PTFE	0.98292	28.52	4.28
Litomos EP-25 grease	0.99251	66.50	4.28

The results of the calculated volume of wear $V_{F(d)}$ for the above regression equations are presented in **Table 3** and graphically illustrated in **Figure 1**. Compatibility of results $V_{F(d)}$ received by means of each of the three calculation methods proves to be correct.

Table 3. Values of the volume of wear function $V_{F(d)}$

Tabela 3. Wartości objętości funkcji zużycia $V_{F(d)}$

Grease:	Volume of wear $V_{F(d)}$ by methods:		
	trapezoids	Simpson 3/8	Simpson 3333/8
car grease 1S	27.8381	27.8346	27.8346
1S grease fulfilled in 6% of tin	25.4315	25.4288	25.4288
1S grease fulfilled in 6% of boron nitride	25.0286	25.0252	25.0252
1S grease fulfilled in 6% of cooper	23.2614	23.2595	23.2595
1S grease fulfilled in 6% of PTFE	19.4437	19.4432	19.4432
Litomos EP-25 grease	18.5968	18.5963	18.5963

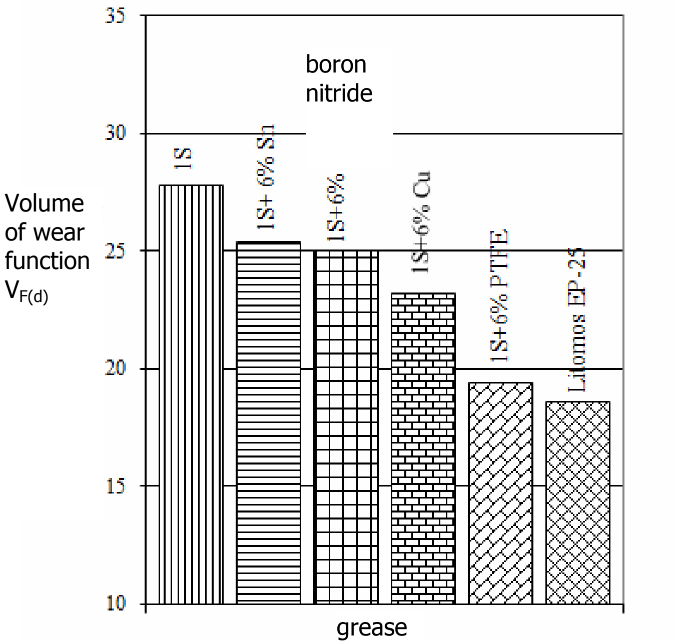

Fig. 1. The volume of the wear function for the tested greases

Rys. 1. Objętość funkcji zużycia dla badanych smarów plastycznych

To summarize the results of the lubrication efficiency of the analysed greases obtained at variable values of pressure and rubbing speed, the following conclusions can be made:

1. The obtained wear regression functions of greases in the area of the variable values of pressure and rubbing speed allow a more precise evaluation of a greases' lubrication efficiency and enables the optimization of the process of selecting a grease for a given values of extortion (p, v) for a steel sliding pair operating in the mixed friction area.
2. The grease lubrication efficiency evaluated on the basis of the volume of wear $V_{F(d)}$ is inversely proportional to the calculated volume – the

reduced volume means lower wear in the studied area of the pressure and rubbing speed extortion.

3. Adopting grease 1S as a REFERENCES base (100%), the following greases are more effective than 1S: a composition of tin is by 9.5% more efficient,
   a composition of boron nitride – by 11.2%, a composition of copper – by 19.6%, a composition of PTFE – by 43.2% and grease Litomos EP 25 by 49.7%.
4. Among the investigated lubricant compositions, the composition of 1S + 6% PTFE showed the most effective lubrication. It is only by 6.5% lower than Litomos EP-25 grease, which one is of the best domestically produced greases.
5. The introduced measure, namely the volume of wear VF (d), certainly reflects the anti-wear characteristics of the lubricant more accurately than the assessment made based on the variation of only one extortion parameter, i.e. the load or rubbing speed. Using this method is particularly appropriate for the selection of a lubricant for nodes working in a wide range of pressures and sliding velocities.

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Streszczenie

Przedstawiono wyniki badań tribologicznych nad efektywnością smarów plastycznych ocenianą na podstawie testów tribologicznych przeprowadzonych przy zmiennych wartościach nacisku *p* i prędkości poślizgu *v*. Za kryterium efektywności przyjęto objętość zużycia $V_{F(d)}$ uzyskanego z równań regresji zużycia (zużycie F(d) = f(F,v)). Zbadano 6 różnych smarów, przy czym dwa z nich to smary plastyczne będące w handlu, a cztery to kompozycje sporządzone na ich bazie z pospolitymi smarami stałymi (PTFE, cyną, miedzią i azotkiem boru). Eksperyment przeprowadzono na aparacie czterokulowym metodą planowanego eksperymentu z wykorzystaniem planu rotalnego na pięciu poziomach. Dla każdego z wytypowanych smarów została opracowana funkcja regresji, która uzależniała zużycie od prędkości poślizgu i obciążenia nadanego. Obliczono objętości otrzymanego zużycia $V_{F(d)}$ i podano stosowne wnioski.