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EFFECT OF PRESSURE AND SLIDING SPEED ON THE FRICTION COEFFICIENT OF POLYURETHANE ELASTOMERS (EPUR) OF DIFFERENT HARDNESS DURING THEIR FRICTION ON STEEL WHEN LUBRICATING WITH GREASE

WPŁYW NACISKU I PRĘDKOŚCI ŚLIZGANIA NA WSPÓŁCZYNNIK TARCIA ELASTOMERÓW POLIURETANOWYCH (EPUR) O RÓŻNEJ TWARDOŚCI PODCZAS ICH TARCIA PO STALI PRZY SMAROWANIU SMAREM PLASTYCZNYM

Key words: polyurethane elastomers (EPUR), grease, mixed friction, coefficient of friction EPUR against steel.

Abstract Polyurethanes (PUR) are widely used for some elements of machinery and equipment, including in motorized shock-absorbing nodes and technical seals that can work in various operating conditions. The article presents the results of tribological investigations of polyurethane elastomers (EPUR) with different hardness (75, 83, and 93 °Sh A), which cooperated with steel in assembly lubrication conditions (mixed friction) with two types of grease (showing low and high adhesion to steel), with variable values of unit pressure *p* and sliding speed *v*. For the research, a rotary plan for two variables (*p* and *v*) was applied at five levels of their value. Based on the results of the tests of particular associations, the regression functions of the form of the second degree polynomial were determined, enabling the development of results in the form of spatial and contour diagrams. Based on the results of tribological tests, recommendations for designers dealing with the design and construction of friction junctions and seals in which polyurethane elastomers cooperating with steel elements can be used.

Słowa kluczowe: elastomery poliuretanowe (EPUR), smar plastyczny, tarcie mieszane, współczynnik tarcia EPUR po stali.

Streszczenie Poliuretany (PUR) znajdują szerokie zastosowanie na niektóre elementy maszyn i urządzeń, między innymi w ruchowych węzłach amortyzujących i uszczelnieniach technicznych, które mogą pracować w różnych warunkach eksploatacyjnych. W artykule przedstawiono wyniki badań tribologicznych elastomerów poliuretanowych (EPUR) o różnej twardości (75, 83 i 93 °Sh A), które współpracowały ze stalą w warunkach smarowania montażowego (tarcie mieszane) dwoma rodzajami smaru plastycznego (wykazujących małą i dużą adhezję do stali), przy zmiennych wartościach nacisku jednostkowego *p* i prędkości ślizgania *v*. Do realizacji badań zastosowano plan rotalny dla dwóch zmiennych (*p* i *v*) na pięciu poziomach ich wartości. Na podstawie wyników badań poszczególnych skojarzeń wyznaczono funkcje regresji o postaci wielomianu drugiego stopnia, umożliwiające opracowanie wyników w postaci wykresów przestrzennych i poziomicowych. Na podstawie wyników badań tribologicznych opracowano zalecenia dla konstruktorów zajmujących się projektowaniem i konstruowaniem ślizgowych węzłów i uszczelnień, w których mogą być zastosowane elastomery poliuretanowe współpracujące z elementami stalowymi.

INTRODUCTION

Polyurethanes are a group of polymers that are formed as a result of reaction between the hydroxyl (OH) groups of a polyol with an isocyanate (NCO) group. This reaction is exothermic and leads to the formation of a urethane group **[L. 1, 2, 3]**. By changing the components and their proportions, one can control the properties of the material obtained so as to receive the required parameters which are inaccessible to other

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elastomers. Because of that, it can be used in special operating conditions **[L. 3, 4]**. Polyurethanes occupy the fifth place in the world in terms of production among polymers **[L. 5]**. Polyurethanes can be in the form of foams, elastomers, varnishes, adhesives, fibres, leather-like materials, as well as lubricants **(Fig. 1) [L. 1, 6, 8]**.

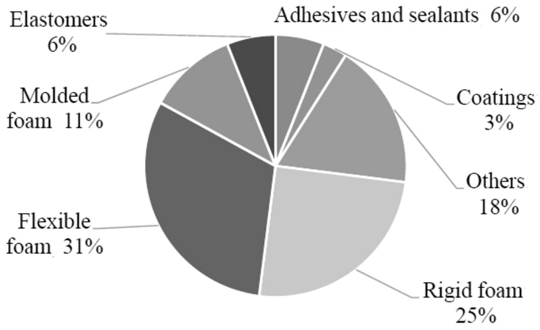

Fig. 1. The use of polyurethanes in the world in 2016 [L. 1]
Rys. 1. Wykorzystanie poliuretanów na świecie w 2016 roku **[L. 1]**

Polyurethane elastomer can be obtained by simultaneously combining polyol, polyisocyanate, and so-called "chain extension" **(Fig. 2) [L. 2]**. Polyurethane elastomers are characterized by good elastic properties (elongation of 600–900% with only 550% rubber) **[L. 3]**, high resistance to tearing and dynamic loads, as well as excellent resistance to abrasive wear **[L. 1, 2]**. It is possible to obtain this elastomer with a wide range of hardness: from 55 °ShA to 70 °ShD **[L. 2]**. EPURs have good shock and vibration damping properties, very good resistance to adverse weather conditions and various oils, greases, liquid fuels, acids or solvents. An additional advantage is that these materials do not stain cooperating elements **[L. 2]**. No other elastomer or even no other polymers possess such a combination of properties **[L. 2, 3]**.

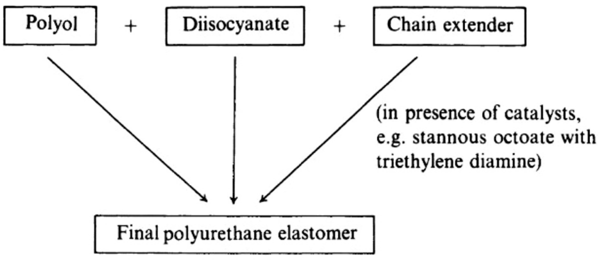

Fig. 2. EPUR production scheme [L. 9]
Rys. 2. Schemat wytwarzania EPUR **[L. 9]**

Polyurethane elastomers play a significant role in the mining, metallurgical, machine, and automotive industries, etc. **[L. 4, 7]**. They found application in the production of transport wheels carrying significant loads, high-strength drive belts, pump parts, seals, as well as shock and vibration dampers, linings for the production of printing rollers and coatings of machine elements and devices resistant to tribological wear **[L. 5]**.

RESEARCH GOAL

Tribological tests were aimed at determining the value of the coefficient of friction of EPUR with different hardnesses (75 °ShA, 83 °ShA and 93 °ShA) in combination with C45 steel under lubrication conditions with selected greases, with varying conditions of unit pressure and sliding speed.

RESEARCH CONDITIONS

The tests were carried out with the following parameters:

- Average unit pressure: p = 0.2 MPa to 0.8 MPa;
- Sliding speed: v = 0.4 m/s to 1.6 m/s;
- Sample material:three polyurethane elastomers (EPUR) with hardness: 75 °ShA, 83 °ShA, 93 °ShA;
- The material of the steel element cooperating with EPUR: C45 steel;
    - steel element hardness: 45 ±1 HRC,
    - steel element roughness: Ra = 0.5–0.6 μm;
- Ambient temperature: T_o = 23 ±1ºC; and,
- Lubricants: sulfonate grease, lithium grease.

Two types of lubricants (sulfonate lubricant and lithium lubricant) were adopted for testing the impact of EPUR-steel lubrication on the friction coefficient **L. 11, 12]**:

- Sulfonate grease (Hutplex EP-2) is produced on the basis of a mineral base oil with the addition of a comprehensive calcium sulfonate thickener, enriched with a package of improvers. It is intended for lubrication of highly loaded rolling bearings of machines and devices operating at medium and high speeds in the temperature range from -20°C to 150°C, periodically up to 180°C **[L. 13]**.
- Lithium grease (ŁT-4S2) is produced on the basis of deeply refined mineral oil, concentrated with lithium soaps. Contains additives improving lubricating properties and additives with anti-corrosive and antioxidant properties. It is intended for the lubrication of rolling bearings, slide bearings, and other machine sets in the operating temperature range from -30°C to 120°C **[L. 14]**.

RESEARCH METHODOLOGY

Research device

In tribological studies of polymer materials, due to their physico-mechanical properties, mainly devices from the surface contact group of the sample with the cooperating element are used. The most common in the world are "pin on disc" devices **[L. 15, 16]**.

Due to the high popularity of this type of device, they can now be considered as standard devices in the field of laboratory testing of polymeric materials, and the results of tribological tests obtained on them can be compared with each other (also internationally) **[L. 15, 16]**.

The tests were carried out on the T-01M "pin on disc" tester **(Fig. 3–5)**. **Figure 3** shows a diagram of a sliding pair, where the sample (1) was loaded with normal force F_N to obtain the desired unit pressure p, and the disc (3) was set in motion at the appropriate rotational speed n, ensuring the required linear speed v on the average path radius r of friction. During the tests, the sample was lubricated with selected plastic greases. The grease was applied with a brush to the surface of the steel element, obtaining a thin film along the entire length of the friction path, and then the testing device was started directly. After 60 seconds of the friction process, the friction force F_T was recorded to determine the coefficient of friction μ. Such a short test time resulted from the assurance of repeatable test results, because with longer friction cooperation, the tested elastomers removed grease from the friction zone and the stick-slip effect occurred. In order to increase the credibility of the test results, the value of the friction force at each point of the experiment plan was determined as the average of three measurements differing by no more than 10% of their value. Tribological studies did not include measurements of wear of the tested elastomers. This was due to the fact that polyurethane elastomers are characterized by very high resistance to abrasive wear and thus, with such a short friction time, the wear of the tested samples was immeasurable by available measurement methods.

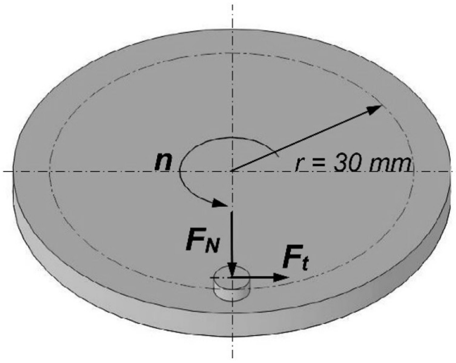

Fig. 3. Functional diagram of the testing device
Rys. 3. Schemat działania urządzenia badawczego

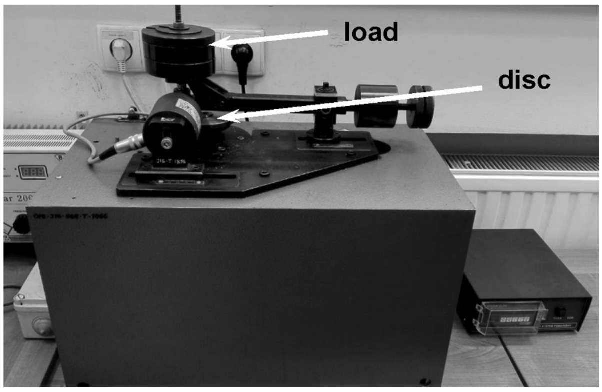

Fig. 4. Test stand with T-01M tester
Rys. 4. Stanowisko badawcze z testerem T-01M

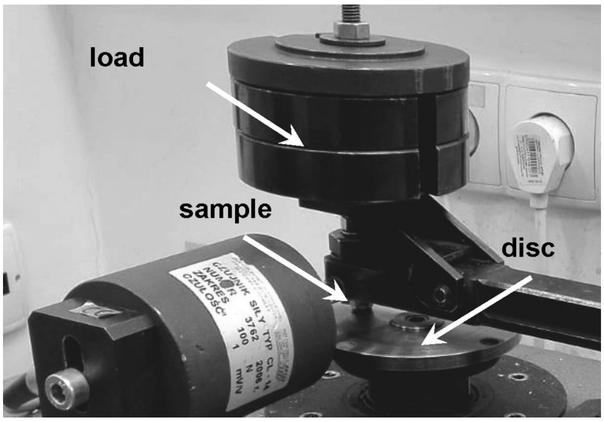

Fig. 5. Test device T-01M – sliding pair
Rys. 5. Urządzenie badawcze T-01M – para ślizgowa

Plan of the research

In multivariate analyses, in order to meet the workload, the costs and duration of research and the techniques of experiment planning and filling of measurable actions are used in terms of the number of operations necessary to a minimum. Planning research consists in determining a series of experiments, i.e. choosing an input matrix for an experiment **[L. 16, 17]**. For designated movements characteristic of linear-quadratic models, it is very useful to use experimental rotational planning with spherical distribution of information, also known as rotational planning and symmetry **[L. 18]**. Unlike other types of multi-level planning, it is characterized by a constant assessment of the regression function in the ranges of the central experiment, guaranteeing constant accuracy of the obtained model. Practically, it is presented that it is a plan of uniform practices with the same variants of the options, which is the same as in the central point of the plan **[L. 16–19]**.

When carrying out an experiment on 5 numbers, the results N are given by the following equation:

$$N = 2^S + 2 \cdot S + N_0 \tag{1}$$

where S – number of experimental input variables,
N_0 – number of tests in the central point of the experiment.

Input x_s (where s = 1, 2, ..., S) have the following values:

$$x_{s(min)},\ x_s^o - \Delta x_s,\ x_s^o,\ x_s^o + \Delta x_s,\ x_{s(max)} \tag{2}$$

where x_{min}, x_{max} – minimal and maximal value of variable "s",
and value of input variable "s" in the central point of the experiment:

$$x_s^o = \frac{x_{s(min)} + x_{s(max)}}{2} \tag{3}$$

value of the basic pitch of the input variable "s" in the experiment plan:

$$\Delta x_s = \frac{x_{s(max)} - x_{s(min)}}{2 \cdot \alpha} \tag{4}$$

α – the value of the star ray, resulting from the rotational condition **[L. 18]**, which for plans for the identification of second degree polynomials is determined from the formula:

$$\alpha = \sqrt[4]{2^S} \tag{5}$$

In rotational plans, the second order polynomial of the following form is usually assumed as the multidimensional regression function:

$$y = b_0 + \sum_{s=1}^{S} b_s \cdot x_s + \sum_{s=1}^{S} b_{ss} \cdot x_s^2 + \sum_{\substack{i=1 \\ j=1 \\ i<j}}^{S} b_{ij} \cdot x_i \cdot x \tag{6}$$

where b_0, b_1, ..., b_s – coefficients of the regression function, S – number of input variables in the experiment, y – output (measured) value in the experiment.

Coefficients of the regression function, presented in the formula (6) are calculated by the method of least squares from the relationship:

$$\mathbf{b} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y} \tag{7}$$

where **X** – experiment matrix, **y** – experiment output vector (measured parameter), **b** – vector of regression coefficients.

The determined regression functions are verified by their statistical assessment, combined with the examination of the adequacy of the regression function from the point of view of the F test and with the examination of the significance of individual elements of the regression function **[L. 18]**.

RESULTS OF THE RESEARCH

The polynomial determined by Formula (6) in the case of two input variables (S = 2), as a multivariate regression function, takes the following form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_1 + b_4x_2x_2 + b_5x_1x_2 \tag{8}$$

where y – output parameter in the research (μ), b_0, b_1, ..., b_5 – coefficients of regression function, x_1, x_2 – variable input values (p, v variables respectively).

Table 1 presents the test plan as the values of unit pressure p and sliding speed v in subsequent test systems from 1 to 13, as well as the values of the coefficient of friction in these test systems, as the initial values in tribological tests of individual EPUR-steel associations, lubricated with sulfonate grease, differing in the hardness of the polyurethane elastomer (75 °ShA, 83 °ShA, 93 °ShA).

Table 1. Plan and results of tribological tests of EPUR-steel combinations lubricated with sulfonate grease
Tabela 1. Plan i wyniki badań tribologicznych skojarzeń EPUR – stal smarowanych smarem sulfonianowym

No.	Input		Output		
			75 °Sh A	80 °Sh A	93 °Sh A
	p [MPa]	*v* [m/s]	Friction coefficient μ[-]		
1	0.288	0.576	0.356	0.317	0.438
2	0.712	0.576	0.531	0.890	0.626
3	0.288	1.424	0.252	0.188	0.315
4	0.712	1.424	0.592	0.582	0.550
5	0.200	1.000	0.235	0.162	0.300
6	0.800	1.000	0.391	0.344	0.536
7	0.500	0.400	0.391	0.298	0.497
8	0.500	1.600	0.357	0.304	0.477
9	0.500	1.000	0.383	0.298	0.483
10	0.500	1.000	0.408	0.327	0.494
11	0.500	1.000	0.496	0.448	0.595
12	0.500	1.000	0.272	0.254	0.392
13	0.500	1.000	0.328	0.481	0.483

Coefficients $b_0 - b_5$ of the regression function (8) calculated according to Formula (7) are presented in **Table 2**, which also contains a statistical assessment of the designated regression functions, which does not provide grounds for the hypothesis about the inadequacy of these functions.

Based on the determined regression functions **(Table 1)**, spatial and level contours of the coefficient of friction change depending on the value of the unit pressure and the sliding speed were prepared, which are presented in **Fig. 6** for EPUR with a hardness of 75 °ShA, in **Fig. 7** for EPUR with a hardness of 83 °ShA, and in **Fig. 8** for EPURs with a hardness of 93 °ShA.

Table 2. Coefficients of the regression function and their statistical evaluation for EPUR-steel lubricated with sulfonate grease

Tabela 2. Współczynniki funkcji regresji i ich ocena statystyczna dla EPUR-stal smarowanych smarem sulfonianowym

No.	Regression coefficient symbol	EPUR hardness		
		75 °Sh A	80 °Sh A	93 °Sh A
		Value of regression coefficient		
1	b_0	0.19268	0.97697	0.39064
2	b_1	-0.1636	-3.2846	-0.5086
3	b_2	0.49121	0.38836	0.40807
4	b_3	0.11716	2.57291	-0.0541
5	b_4	-0.0473	-0.0617	-0.1631
6	b_5	-0.3962	-0.0017	0.26034
Statistical evaluation of regression function				
Standard deviation		0.1060	0.1913	0.0971
Correlation coefficient R		0.9937	0.9324	0.9642
F-Test	for $\alpha = 0.05$ $F_{crit} = 3.97$ for $\alpha = 0.01$ $F_{crit} = 5.67$	109.21	9.32	18.51

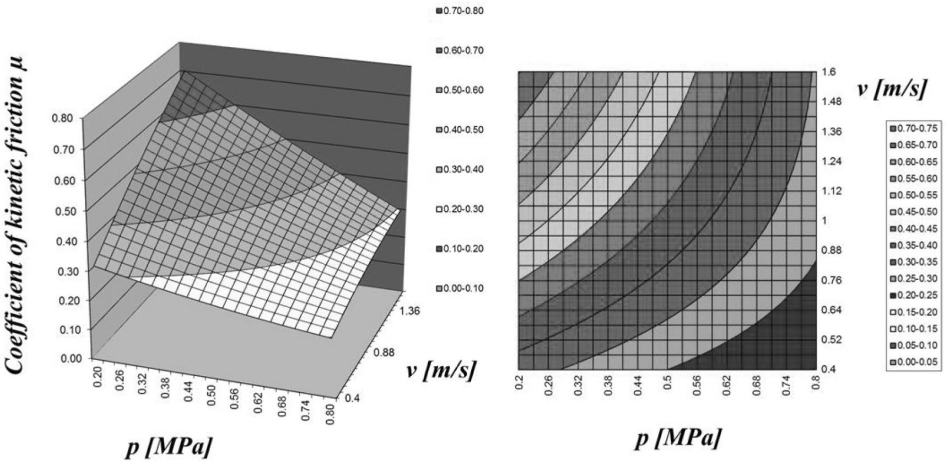

Fig. 6. Coefficient of friction EPUR with a hardness of 75 °Sh A against steel lubricated with sulfonate grease

Rys. 6. Współczynnik tarcia EPUR o twardości 75 °Sh A po stali w obecności smaru sulfonianowego

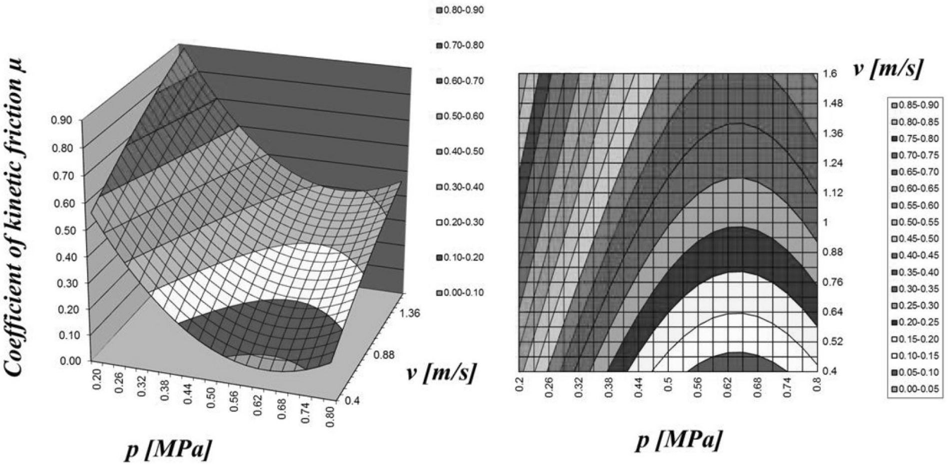

Fig. 7. Coefficient of friction EPUR with a hardness of 83 °Sh A against steel lubricated with sulfonate grease

Rys. 7. Współczynnik tarcia EPUR o twardości 83 °Sh A po stali w obecności smaru sulfonianowego

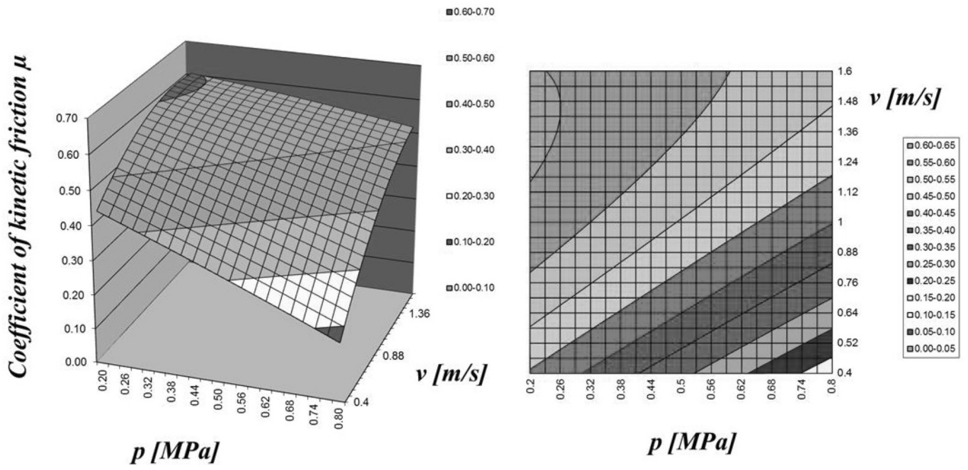

Fig. 8. Coefficient of friction EPUR with a hardness of 93 °Sh A against steel lubricated with sulfonate grease
Rys. 8. Współczynnik tarcia EPUR o twardości 93 °Sh A po stali w obecności smaru sulfonianowego

Similarly as in the case of sulfonate grease lubrication, **Table 3** presents the results of tribological tests of individual EPUR-steel associations, differing in the hardness of the polyurethane elastomer (75 °ShA, 83 °ShA, 93 °ShA), which were lubricated with lithium grease.

Table 3. Plan and results of tribological tests of EPUR-steel combinations lubricated with lithium grease
Tabela 3. Plan i wyniki badań tribologicznych skojarzeń EPUR–stal smarowanych smarem litowym

No.	Input		Output		
			75 °Sh A	80 °Sh A	93 °Sh A
	p [MPa]	*v* [m/s]	Friction coefficient *μ*[-]		
1	0.288	0.576	1.054	0.960	0.896
2	0.712	0.576	1.059	0.745	0.902
3	0.288	1.424	0.717	0.298	0.559
4	0.712	1.424	0.914	0.810	0.802
5	0.200	1.000	0.747	0.503	0.463
6	0.800	1.000	0.899	0.803	0.759
7	0.500	0.400	0.957	0.778	0.641
8	0.500	1.600	0.993	0.834	0.632
9	0.500	1.000	1.010	0.784	0.758
10	0.500	1.000	1.048	0.742	0.883
11	0.500	1.000	0.963	0.893	0.795
12	0.500	1.000	0.563	0.643	0.672
13	0.500	1.000	0.739	0.609	0.942

Also in this case coefficients $b_0 - b_5$ of regression function (8) calculated from the formula (7) and their statistical evaluation are shown in the **Table 4**.

Table 4. Coefficients of the regression function and their statistical evaluation for EPUR-steel lubricated with lithium grease
Tabela 4. Współczynniki funkcji regresji i ich ocena statystyczna dla EPUR–stal smarowanych smarem litowym

No.	Regression coefficient symbol	EPUR hardness		
		75 °Sh A	80 °Sh A	93 °Sh A
		Value of regression coefficient		
1	b_0	0.58805	1.17808	1.60703
2	b_1	0.87483	-2.062	-2.7758
3	b_2	0.6866	0.10094	-0.3865
4	b_3	-1.9431	0.17507	0.82089
5	b_4	0.4063	-0.2841	-0.0985
6	b_5	0.37012	1.56112	1.59036
Statistical evaluation of regression function				
Standard deviation		0.1621	0.1679	0.1456
Correlation coefficient R		0.9171	0.9069	0.9030
F-Test	for α = 0.05 F_{crit} = 3.97 for α = 0.01 F_{crit} = 5.67	7.41	6.48	6.19

Statistical evaluation of the designated regression functions, also in the discussed case, with lithium grease lubrication, does not give grounds for accepting the hypothesis about the inadequacy of these functions. Therefore, the designated regression functions **(Table 3)** enabled the drawing of spatial and contour-level coefficient of friction changes depending on the value of the unit pressure and the sliding speed, which are presented in **Figs. 9, 10,** and **11** for EPURs with hardness 75 °ShA, 83 °ShA and 93 °ShA.

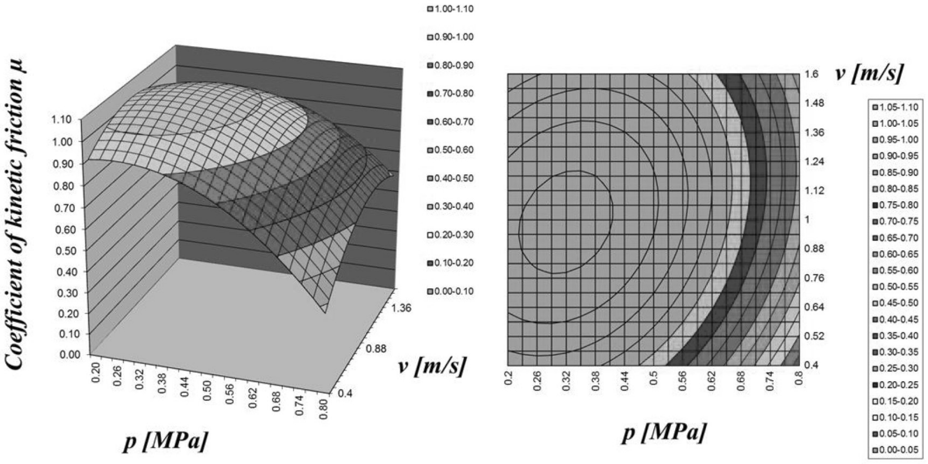

Fig. 9. Coefficient of friction EPUR with a hardness of 75 °Sh A against steel lubricated with of lithium grease
Rys. 9. Współczynnik tarcia EPUR o twardości 75 °Sh A po stali w obecności smaru litowego

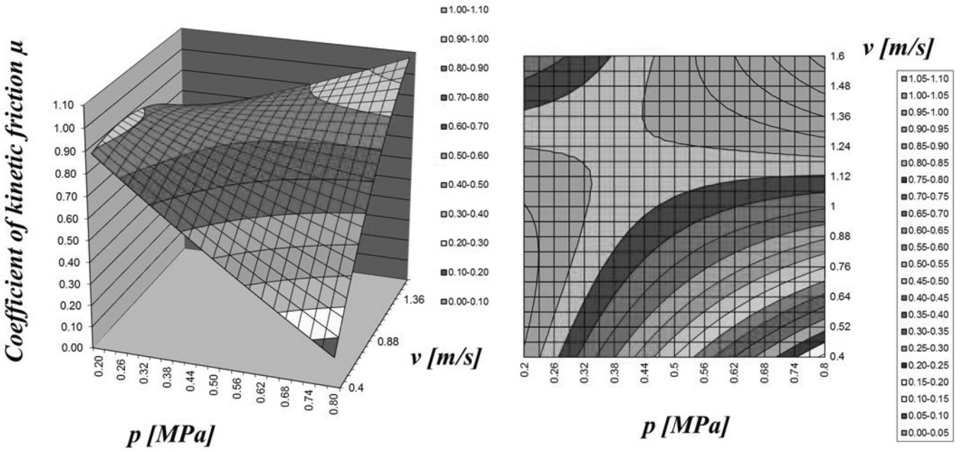

Fig. 10. Coefficient of friction EPUR with a hardness of 83 °Sh A against steel lubricated with of lithium grease
Rys. 10. Współczynnik tarcia EPUR o twardości 83 °Sh A w obecności smaru litowego

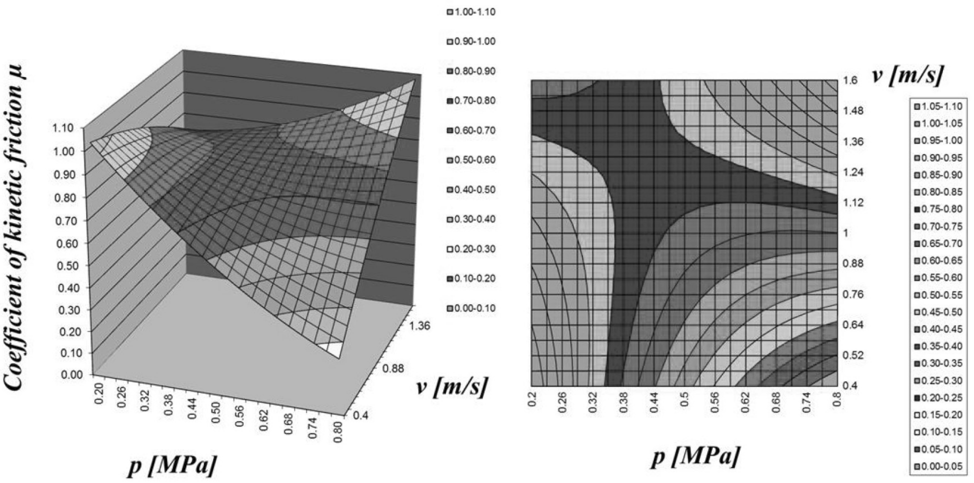

Fig. 11. Coefficient of friction EPUR with a hardness of 93 °Sh A against steel lubricated with of lithium grease
Rys. 11. Współczynnik tarcia EPUR o twardości 93 °Sh A po stali w obecności smaru litowego

SUMMARY

From the comparison of obtained graphs and analysis of the change in the value of the coefficient of friction together with the changes in the value of the unit pressure *p* and the sliding speed *v* **(Figs. 6–11)**, a tendency can be observed to increase the value of the coefficient of friction along with a decrease in the hardness of EPUR cooperating with a steel element in lubrication conditions both adopted for testing with greases. It was caused by a larger real contact surface with a steel EPUR element of lower hardness and more effective removal of grease from the friction zone, which in turn influenced the increase in adhesion resulting in an increase in the coefficient of friction. With a longer friction time than the one in which the measurements were carried out, there was even observed a stick-slip effect.

The increase in unit pressure resulted in a decrease in the value of the coefficient of friction, referred to as F_t/F_N **(Fig. 3)**, which resulted from the fact that, in the case of mixed friction, the increase in friction force F_t is not proportional to the increase in normal load F_N (the friction force increases only slightly in relation to the increase in normal load). However, as the sliding speed increases, the coefficient of friction increases, which was observed in all types of tested EPUR–steel combinations lubricated with both types of greases. This effect was caused by the increase in temperature in the friction zone along with the increase of the sliding speed. As a result, grease was removed from the friction zone and the friction force increased. During the tests, no temperature was recorded in the friction area, but strong heating of the cooperating friction steel element was observed, leading to the transition of the lubricant to the liquid state. This process was of avalanche nature, i.e. greater friction (friction work) generated an increase in friction heat, which in turn reduced the consistency of lubricants and removed them from the friction path even faster, resulting in an increase in the coefficient of friction. Tribological studies have shown that more effective lubricant due to the possibility of reducing the coefficient of friction of EPUR–steel associations is sulfonate grease, characterized by a slightly higher permissible operating temperature and less susceptibility to reducing consistency during friction compared to lithium grease.

In conclusion of the conducted tests, it should be stated that polyurethane elastomers should be used in sliding nodes with lubrication of greases in the range of low sliding speeds up to approx. 0.5–0.7 m/s, while higher values of this speed are allowed for EPUR with higher hardness.

Based on the obtained test results, recommendations can be made regarding the use of EPUR in motor friction nodes with steel under grease lubrication conditions:

1. The EPUR–steel associations constituting the movement friction nodes should cooperate in the conditions of lubrication with lubricants, including assembly lubrication with greases, which results from ensuring their beneficial frictional cooperation, eliminating stick-slip effect.
2. The more effective lubricant during assembly lubrication of EPUR–steel associations turned out to be sulfonate grease, which was due to the greater possibility of maintaining the lubricant film in the friction area with the increase of friction process forces, mainly sliding speed.
3. The recommended sliding speed in friction joints EPUR–steel lubricated with tested greases should not exceed the value of about 0.5 to 0.7 m/s due to the possibility of the formation of an adverse stick-slip effect resulting from the removal of grease from the friction zone.
4. In EPUR–steel sliding friction nodes lubricated with grease, polyurethane elastomers having higher hardness should be used, due to their lower coefficient of friction in such sliding associations.

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