Research Article

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Effect of contact pressure and sliding speed on the friction of polyurethane elastomer (EPUR) during sliding on steel under water wetting conditions

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1 Introduction

Due to its properties, polyurethane (PUR) has been widely used for many years for various machine and device components [12, 16]. Especially in recent years, thanks to the introduction of new PUR technologies with very diverse properties, there is an even greater interest in the usage of this material. Polyurethanes can be produced as foams, rubbers (cast, thermoplastic and rolled elastomers), varnishes, glues, fibers and leather-like materials, applicable in almost all areas of life and economy [14].

The polyurethanes are essentially obtained by reacting the polyesters or polyethers containing free hydroxyl groups (polyols) with diisocyanates together with added auxiliaries. The combination and mixing of these ready-to-process components with auxiliary materials, such as, for example, catalysts, foaming agents, stabilizers, initiates a chemical reaction leading to the production of PUR. By changing the components and their proportions, one can adjust the properties of the resulting polyurethane, so as to obtain a material with the required stiffness or elasticity, suitable for specific, individual applications [12, 16]. Depending on the conditions of the reaction, the type and amount of components, products with different properties are obtained, e.g. polyurethane elastomers (EPUR) of different hardness [6, 14].

Polyurethane elastomers are rubber-like in form, and are characterized by good mechanical properties and excellent resistance to abrasive wear [4], the highest among all polymeric materials [6, 9?]. What is more, polyurethanes are as well characterized by excellent resistance to mineral oils, fats, gasoline, organic solvents, solutions of acids and bases, as well as light radiation (including UV radiation). Polyurethanes have self-extinguishing properties (they are non-flammable), electro-insulating, they do not stain other elements. Additionally in the atmosphere of oxygen and ozone those materials are not aging. PUR are six times lighter than steel and can work continuously while maintaining their flexibility in the temperature range from -30°C to $+120^{\circ}\text{C}$ [6].

Polyurethane elastomers perfectly dampen mechanical vibrations, which is why they are used for elastic machine elements, such as inserts of flexible couplings, bumpers, anti-vibration pads, wheel treads, as well as for technical sealing elements. EPUR are now increasingly widely used, among others in damping connections and both stationary and moveable technical seals, which can work in various operating conditions. They cooperate most often in associations with steel elements in which the coefficient of friction, both static and kinetic, plays a significant role in the proper cooperation of cushioning joints or effective sealing [15]. The coefficient of friction in such associations significantly depends on the EPUR hardness and the frictional conditions of cooperation, e.g. the type of lubrication or its absence or ambient conditions, as well as the influence of temperature, humidity, water, etc. [13]. During static friction the coefficient of friction also depends on the value of pressure and time of stationary contact under loading [8], and in the case of kinetic friction also on unit pressure and sliding speed [2, 3, 15].

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2 Assumptions for tribological tests

2.1 Purpose of the research

The tribological tests were to include the determination of the EPUR coefficient of friction with hardness: 75, 80 and 93 °Sh A, in combination with C45 steel both under conditions of technically dry friction and during wetting of the friction pair with water. However, preliminary tribological tests showed that these tests cannot be carried out in conditions of dry steel and friction, due to the occurrence of the “stick-slip” phenomenon, especially manifested in the case of EPUR with low hardness, that is why this part of the research was abandoned. EPUR tribological tests (with different hardness) in combination with steel, were carried out only under conditions of wetting the friction pair with water, in the range of different unit pressure values $p = 0.2\text{--}0.8\text{ MPa}$ and sliding velocity $v = 0.4\text{--}1.6\text{ m/s}$. Due to the high resistance of EPUR to tribological wear, in the conducted research the determination of the value of EPUR sample wear was waived, because it would have required very long-term research to determine wear with adequate accuracy.

2.2 Materials for the research

Samples for tribological tests in the form of discs (mandrels) size $\varnothing 8 \times 3\text{ mm}$ were cut from sheets (3 mm thick) EPUR with hardness: 75, 80 and 93 °Sh A. Slip partners of the associations, disc-shaped, were made of heat-treated C45 steel up to hardness of 44–46 HRC and ground perimeters to obtain a roughness parameter R_a in the range of $0.5\text{--}0.6\text{ }\mu\text{m}$.

2.3 Research device

For tribological tests a T-01M pin-on-disc tribometer [10] was used, the diagram of which is shown in Figure 1. Sample 1 was loaded with normal force F_N to obtain the desired unit pressure p , and disc 3 was given the appropriate rotational speed n to obtain the required linear speed v . During the tests, the disc was wetted with water continuously using a tampon. After the friction process has stabilized, the friction force F_t was measured to determine the friction coefficient μ .

Figure 1: Scheme of pin-on-disc tribometer.

2.4 Research methodology

The purpose of the work was to determine the influence of two input parameters: unit pressure p and sliding velocity v on the value of the coefficient of friction of polyurethane elastomers of different hardness in combination with a steel element during lubrication with water. The experimental design methodology was adopted for the implementation of the research, in which a rotational plan was applied on five levels for two input quantities. The rotary plan is designed for linear-quadratic models, most often found in technical facilities. It is a plan with a spherical information distribution, also called a plan with rotational symmetry. Its important advantage, compared to other types of multilevel plans, is that it is characterized by a constant variance of the regression function around the central point of the experiment. It is practically assumed that it is a uniformly accurate plan, with the same variance, the same as in the central point of the plan [1–3, 11].

When implementing the experiment on 5 levels, the number of N experiments is determined by the formula:

$$N = 2^S + 2 \cdot S + N_0 \quad (1)$$

where: $S = 2$ – number of input variables,

$N_0 = 5$ – number of test in the central point of the experiment [11].

Input values x_s (where $s = 1, 2, \dots, S$) have following values:

$$x_{S(\min)}, x_s^0 - \Delta x_s, x_s^0, x_s^0 + \Delta x_s, x_{S(\max)} \quad (2)$$

where:

$x_{S(\min)}, x_{S(\max)}$ – minimum and maximum values of variable S , and:

value of input variable $\sin$ the central point of the experiment:

$$x_s^0 = \frac{x_{S(\min)} + x_{S(\max)}}{2} \quad (3)$$

the value of basic increment of input variable $\sin$ experimental plan:

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

Table 1: Experimental plan and results of testing the coefficient of friction of different hardness EPUR.

No.	Input values		Output values		
	p [MPa]	v [m/s]	75° Sh A	80° Sh A Coefficient of friction μ [-]	93° Sh A
1	0.288	0.576	0.497	0.570	0.320
2	0.712	0.576	0.137	0.241	0.568
3	0.288	1.424	0.211	0.320	0.255
4	0.712	1.424	0.066	0.037	0.137
5	0.200	1.000	0.651	0.630	0.367
6	0.800	1.000	0.117	0.248	0.202
7	0.500	0.400	0.249	0.162	0.373
8	0.500	1.600	0.092	0.068	0.205
9	0.500	1.000	0.163	0.044	0.232
10	0.500	1.000	0.155	0.015	0.227
11	0.500	1.000	0.144	0.025	0.230
12	0.500	1.000	0.169	0.016	0.235
13	0.500	1.000	0.150	0.041	0.237

α - the value of the stellar radius, resulting from the condition of rotaliness [11], which for plans for identification of second degree polynomial is defined by the formula:

$$\alpha = \sqrt[4]{2^S} \quad (5)$$

In rotational plans as multidimensional regression function second degree polynomial in such form is used:

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

where: $b_0, b_1, \dots, b_s$ – parameters of the regression function,

S – number of input variables (p, v),

y – output values (measured) from experiment (coefficient of friction of tested EPUR elastomers with different hardness in combination with a steel element EPUR elastomers with different hardness in combination with a steel element).

Coefficients of the regression function (for $S = 2$ number of coefficients is 6), are calculated by the least squares method, using the following formula:

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

where: $\mathbf{X}$ – the matrix of the experiment,

$\mathbf{y}$ – vector of experiment outputs (measured values),

$\mathbf{b}$ – vector of regression function parameters.

In the case of $S = 2$ and $N_0 = 5$, the number of experiments to complete the multidimensional regression function will be $N = 13$.

The determined regression functions are verified by their statistical evaluation, combining the adequacy of the regression function from the point of view of the F test and the significance of the regression functions' elements from the point of view of the t-test [11].

2.5 Test conditions

The research focused on determining the influence on the coefficient of friction of the tested combinations of two input factors of the experiment, i.e. the unit pressure p and the sliding velocity v , defined in point 2.4 as variables: x_1, x_2 , which according to the relationship (2) assumed the following values:

for x_1 – unit pressure p [MPa]:

$$x_{1 \min} = 0.2; x_1^0 - \Delta x_1 = 0.288; x_1^0 = 0.5; x_1^0 + \Delta x_1 = 0.712; x_{1 \max} = 0.8$$

for x_2 – sliding speed v [m/s]:

$$x_{2 \min} = 0.4; x_2^0 - \Delta x_2 = 0.576; x_2^0 = 1.0; x_2^0 + \Delta x_2 = 1.424; x_{2 \max} = 1.6.$$

The total plan layouts, constituting the input matrix of the $\mathbf{X}$ experiment, are presented in Chapter 3 in Table 1 as input values

3 Results of tests

The results of tribological tests, being the values of the EPUR friction coefficient after water wetted steel, for individual experimental systems differing in p and v values, are presented in Table 1 as the experiment y output vectors for individual EPUR hardnesses (columns of output values in Table 1).

On the basis of the obtained test results, using formula (7), the coefficients $b_0 \dots b_5$ of regression function $y = f(x_1, x_2)$ were calculated. It showed the dependence of the change of the EPUR coefficient of friction (three different values of hardness) on the steel moistened with water on unit pressure and velocity of sliding (x_1 i x_2) in the form of a second degree polynomial for two input variables:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_1 + b_4x_2x_2 + b_5x_1x_2 \quad (8)$$

where: $b_0 \dots b_5$ – regression function coefficient.

Regression function enabled the analysis of the experimental results by comparison and analysis of charts of two variables: p and v for different EPUR hardness: 75, 80 and 93 °Sh A, shown in Figure 2-4.

4 Summary and conclusions

Preliminary tribological study showed that there are limited possibilities in application of EPUR combined with steel in dry friction conditions. Particularly for low hardness EPUR, for which “stick-slip” phenomenon occurs. “Stick-slip” phenomenon is caused mostly by specific mechanical properties of EPUR and significant difference in static and kinetic friction coefficient in dry friction conditions. For that reason application of EPUR in kinematic pair in dry friction conditions with steel is not recommended. That is why the authors resigned from planned study in such conditions. On the other hand, EPUR with various values of hardness can be successfully used in static pairs in such conditions [6].

Basing on the results of the research it was observed a significant impact of EPUR hardness on values of coefficient of friction with steel in water-wetting condition, under different pressure and with different sliding speed. For EPUR hardness up to 80 °Sh A values of friction coefficient decreased with increase of unit pressure (without influence of changes of sliding speed). Initial values of coefficient of friction were 0.5-0.6 and they lowered to 0.1-0.15 for pressure of 0.6-0.7 MPa (Figure 2 and Figure 3). In case of EPUR with greater values of hardness (93 °Sh A) similar influence of pressure on coefficient of friction was no-

ticed for sliding speeds from 0.8 m/s. Increase of pressure from the range of 0.2-0.8 MPa coefficient of frictions lowered from 0.3-0.45 to 0.1-0.25. A different dependence occurred at low values of sliding speed (up to 0.8 m/s), where increase of unit pressure resulted in rise of coefficient of friction from 0.3 to 0.5-0.6 (Figure 4).

Based on the analysis of the results of tribological tests of polyurethane elastomers of different hardness cooperating with a steel element wetted with water, in various conditions of unit pressure and sliding speed, the following conclusions were formulated:

1. Possibility of “stick-slip” phenomenon in conditions of friction of technically dry polyurethane elastomers of low hardness with a steel element, may cause significant restrictions in the use of such associations during their moving cooperation.
2. Moving connections of polyurethane elastomers with a steel element under water wetting conditions do not show the phenomenon of “stick-slip”. Their tribological cooperation appears to be more favorable as compared to technically dry friction. One can assume that similar effects will occur in the case of friction of these associations while lubricated, e.g. with oils or greases.
3. The results of tribological tests presented in the form of diagrams, shown in Figures 2 to 4, enable the selection of appropriate values of unit pressure p and sliding velocity v to ensure appropriate friction coefficient values for individual combinations of polyurethane elastomers of different hardness with a steel element moistened with water.

The results are particularly important due to the lack of available results of tribological tests of EPUR-steel in water in the literature. This is the starting point for further study in which the oil or grease will be used as a lubricant. This research will allow the simulation of the work of real friction nodes of machines in which the given materials could be used. The need for such study is related to growing use of EPUR as a material in such important connections as exposed to the intense wear of the kinematic pair. A potential area of application of these materials may be friction nodes of mining machinery and equipment.

References

- [1] Capanidis D.(2007). Selected aspects of the methodology of tribological investigations of polymer materials. Archives of Civil and Mechanical Engineering, 7 (4), 39-55.

Figure 2: Coefficient of friction of EPUR with hardness of 75 °Sh A after steel dampened with water depending on the pressure p and sliding speed v

Figure 3: Coefficient of friction of EPUR with hardness of 80 °Sh A after steel dampened with water depending on the pressure p and sliding speed v .

- [2] Capanidis D. (2013). Elementy ślizgowe uszczelnień. *Hydraulika i Pneumatyka*, 6, 17-20 (in Polish).
- [3] Capanidis D. (2013). Mechanizm tarcia i zużywania wielokomponentowych kompozytów na podstawie polioksymetyleny. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej (in Polish).
- [4] Capanidis D. (2016). The influence of hardness of polyurethane on its abrasive wear resistance. *Tribologia*, 47, (4), 29-39.
- [5] Capanidis D., Kowalewski P., Krauze M. (2016). Study of resistance to abrasive wear of multicomponent polyoxymethylene composites. *Tribologia*, 47 (1), 7-19.
- [6] Capanidis D., Kowalewski P., Krauze M., Zięba K. (2016). Wpływ parametrów wytwarzania pianki PUR na jej twardość w aspekcie zastosowania na uszczelnienia spoczynkowe, In: *Uszczelnienia i technika uszczelniania maszyn i urządzeń: XIV międzynarodowa konferencja naukowo-techniczna* Seals and sealing technology of machines and devices, pod red. Marka Gawlińskiego Wrocław: SIMP Oddział we Wrocławiu, 72-83 (in Polish).

Figure 4: Coefficient of friction of EPUR with hardness of 93 °Sh A after steel dampened with water depending on the pressure p and sliding speed v

Table 2: Coefficients of the regression function and statistical evaluation of the designated functions.

No.	Symbol of the regression function coefficient	EPUR hardness		
		75° Sh A	80° Sh A	93° Sh A
Values of the regression function coefficient				
1	b ₀	1.532438791	2.026949852	0.366320127
2	b ₁	−3.597305085	−5.448645559	0.189574402
3	b ₂	−0.41274929	−0.760401273	−0.116951409
4	b ₃	2.256693292	4.643720166	0.764795034
5	b ₄	−0.028481923	0.262086202	0.204277042
6	b ₅	0.598867086	0.126098629	−1.014933527
Statistical evaluation of the regression function				
	Standard deviation	0.1685	0.2103	0.1098
	Correlation coefficient R	0.9773	0.9860	0.9012
F-test	for $\alpha = 0.05$ F _{kr} = 3.97			
	for $\alpha = 0.01$ F _{kr} = 5.67	29.76	49.04	6.05

- [7] Capanidis D., Kowalewski P., Leśniewski T., Paszkowski M., Wieleba W. (2015). Rola badań tribologicznych w aspekcie zwiększania trwałości i niezawodności eksploatacyjnej maszyn i urządzeń użytkowanych w Zagłębiu Miedziowym. Zeszyty Naukowe Dolnośląskiej Wyższej Szkoły Przedsiębiorczości i Techniki. Studia z Nauk Technicznych, 4, 47-64 (in Polish).
- [8] Capanidis D., Kowalewski P., Wieleba W. (2010, May 26-28). Wpływ wartości nacisku oraz czasu jego działania w okresie spoczynku na współczynnik tarcia statycznego PA i POM po stali. Paper presented at Międzynarodowa XII Konferencja Naukowo-Techniczna: Uszczelnienia i technika uszczelniania maszyn i urządzeń, (Wrocław - Kudowa Zdrój, Poland), 50-58 (in Polish).
- [9] Capanidis D., Wieleba W. (2009). Badania odporności na ścieranie materiałów polimerowych stosowanych na opakowania transportowe. Czasopismo Techniczne. M, Mechanika, 106 (1M), 51-55 (in Polish).
- [10] Catalogue of Institute of Sustainable Technologies - National Research Institute in Radom <http://www.katalog.itee.radom.pl/images/stories/karty/56.t-01m.pdf> (in Polish).
- [11] Mańczak K. (1976). Technika planowania eksperymentu, Warszawa: WNT (in Polish).
- [12] Olczyk W. (1968). Poliuretany, Warszawa: Wydawnictwa Naukowo-Techniczne (in Polish).
- [13] Ptak A., Wieleba W., Kowalewski P., Capanidis D. (2011). Wpływ wilgotności i temperatury powietrza na współczynnik tarcia statycznego wybranych par ślizgowych metal-polimer. Tribolo-

gia, 42 (5), 181-188 (in Polish).

- [14] Rokicki G., Ryszkowska J., Prociak A. (2014). *Materiały poliuretanowe*, Warszawa: Wydawnictwo Naukowe PWN (in Polish).
- [15] Wieleba W., Capanidis D., Kowalewski P., Paszkowski M. (2011). *Materiały polimerowe w uszczelnieniach - tarcie statyczne. Hydraulika i Pneumatyka*, 6, 10-13 (in Polish).
- [16] Żuchowska D. (1993). *Polimery konstrukcyjne. Przetwórstwo i właściwości*. (Wyd. 2 zm.), Wrocław: Politechnika Wrocławska (in Polish).