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Mariusz OPAŁKA[*], **Wojciech WIELEBA**[**], **Angelika RADZIŃSKA**[***]

INFLUENCE OF THE DYNAMICS OF FORCED MOTION ON THE STATIC FRICTION IN METAL-POLYMER SLIDING PAIRS

WPŁYW DYNAMIKI WYMUSZENIA RUCHU NA OPORY TARCIA STATYCZNEGO W PARACH ŚLIZGOWYCH METAL–POLIMER

Key words: dynamics of start, sliding polymers, friction.

Abstract: The resistance during the frictional interaction of polymeric materials with metallic materials is characterized by a significant dependence on the dynamics of the motion inputs. In a metal-polymer friction pair, the static friction resistance during standstill under load depends on the rate of growth of the force causing the relative motion. Tribological tests of selected (polymer-metal) sliding pairs were carried out. The selected polymers were polyurethane (TPU), polysulfone (PSU), and silicone rubber (SI). They interacted with a pin made of normalized C45 steel under unitary pressure $p = 0.5$ MPa in dry friction conditions at different gradients of the force driving the relative motion ($dF/dt = 0.1$-20 [N/s]). The static friction coefficient of the selected sliding pairs was determined on the basis of the recorded static friction force values. The test results show a significant influence of the rate of increase in the motion driving force on the values of static friction resistance. This is mainly due to the viscoelastic properties of polymers.

Słowa kluczowe: dynamika ruchu, polimery ślizgowe, tarcie.

Streszczenie: Opory podczas współpracy ciernej materiałów polimerowych z materiałami metalicznymi cechują się znaczną zależnością od dynamiki wymuszeń ruchu. Podczas postoju pod obciążeniem pary trącej metal–polimer, opory tarcia statycznego są zależne od prędkości narastania siły wywołującej ruch względny. Przeprowadzono badania tribologiczne wybranych par ślizgowych (polimer–metal). Polimerami wybranymi do badań były: poliuretan (TPU), polisulfon (PSU) oraz guma silikonowa (SI). Współpracowały one trzpieniem wykonanym ze stali C45 w stanie normalizowanym dla nacisku jednostkowego $p = 0,5$ MPa w warunkach tarcia suchego dla różnych gradientów przyrostu siły wymuszającej ruch względny $dF/dt = 0,1 – 20$ N/s. Na podstawie rejestrowanych wartości siły tarcia statycznego wyznaczony został współczynnik tarcia statycznego wybranych par ślizgowych. Wyniki badań ukazują znaczący wpływ prędkości narastania siły wymuszającej ruch na wartości oporów tarcia statycznego. Głównym powodem takiego stanu rzeczy są lepko-sprężyste własności polimerów.

INTRODUCTION

Polymer materials are widely used for machine components and parts which must meet high technical requirements or do not have to meet so high requirements (e.g., covers performing aesthetic functions). Owing to their many unique properties, plastics are often used as sliding elements in various friction nodes – from technical seals, through bearings to gears. But plastics have a certain characteristic, stemming from their internal structure, which significantly affects their functional properties. This characteristic is viscoelasticity. Depending on the equilibrium

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[*] ORCID: 0000-0002-0675-9822. Wroclaw University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

[**] ORCID: 0000-0002-5461-9568. Wroclaw University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland.

[***] ORCID: 0000-0001-9035-2963.

state (glassy, forced elasticity, highly elastic), the viscosity characteristic influences the mechanical properties of the plastic to a different degree.

Because of their viscoelastic properties, the behaviour of plastics depends on the type and value of the loads applied to them, and on the way in which the loads reach their nominal values. This paper analyses the influence of the rate at which the force causing the relative motion of sliding pair is increased on the values of static friction resistance in simple metal-elastomer sliding pairs. The course of the friction process is influenced by many variables **[L. 1]**. So far, the above-mentioned influence of the rate at which the tangential force (causing the sliding of a friction pair) is increased has not been discussed more widely for metal-polymer combinations.

The influence of the sliding velocity on the value of the friction force has been frequently discussed in the literature on frictional resistance. For example, Wu J. et al. analysed the influence of the sliding velocity on the value of the (static and kinetic) friction force for rubber **[L. 2]**. Persson et al. analysed the influence of the sliding velocity on motion resistance on the nanoscale **[L. 3]**. This influence is most significant in the case of the frictional interaction between materials with distinct viscoelastic properties **[L. 4]**.

Ptak A. has extensively studied the effect of negative temperatures on the frictional resistance of polymers **[L. 5–8]**. The test results showed that lowering the temperature from 0°C to -50°C led to a decrease in the value of the friction coefficient in the tested materials (PA6, PEEK, PTFE). This is due to the fact that, as a result of cooling, the material's stiffness increases, whereby the mechanical impact (the deformation of the polymer) decreases, and so does the friction coefficient.

Another parameter influencing the frictional resistance of metal-polymer sliding pairs is the unit pressure in the contact zone of the sliding pair **[L. 8–12]**. For metal-metal combinations, the contact surface depends only on the load and its distribution on the contact surface. In contrast, in the case of polymers (materials with clear viscoelastic properties), the contact surface depends not only on the load, but also on the time of its operation. The general dependence of the friction coefficient on pressure for metal-polymer sliding pairs is presented in **Fig. 1**.

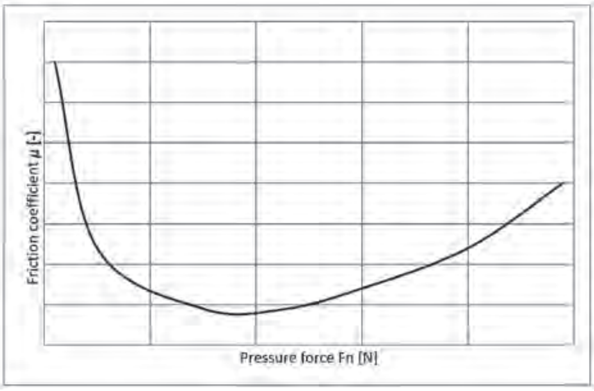

Fig. 1. General dependence of friction coefficient on pressure force for metal-polymer pairs [L. 13, 14]

Rys. 1. Ogólna zależność współczynnika tarcia od siły nacisku dla skojarzeń metal–polimer **[L. 13, 14]**

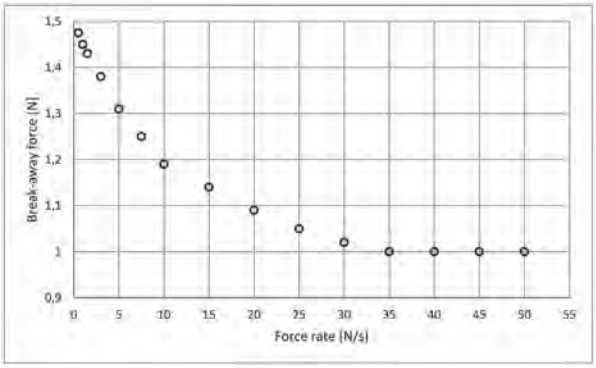

Fig. 2. Rate of increase in tangential force versus static friction force [L. 15]

Rys. 2. Zależność pomiędzy prędkością narastania siły stycznej a siłą tarcia statycznego w skojarzeniu ciernym **[L. 15]**

Kujawa M. analysed the influence of the deformation state of polymeric elements on the values of frictional resistance and wear in metal-polymer pairs **[L. 16, 17]**. He showed that even a slight deformation (of 2%) reduces the microhardness of the polymer, which leads to an increase in wear by up to 51% (for PE-HD).

Johannes et al. **[L. 18]** investigated the effect of the standstill time under load and the rate of increase in the tangential force on the value of the static friction coefficient in the steel-steel combination during the stick-slip phenomenon. They showed that the time of standstill under load alone does not describe the observed changes in static friction resistance in detail. Similar studies were carried out by Richardson and Nolle **[L. 19]** et al. **[L. 15]**, who showed that for high rates of tangential force growth in the sliding pair the standstill time under load is not important. They also showed that, in steel-steel combinations in dry friction conditions, as the tangential force velocity increases, the value of the static friction coefficient decreases logarithmically until it reaches a certain critical value and becomes stabilized.

The influence of the rate of increase in the motion driving force on static friction resistance in polymer-metal friction pairs has not been sufficiently described in the literature. But this is a significant problem affecting the start-up of tribological systems with polymer-metal sliding combinations. Therefore, the aim of this study was to determine this influence.

MATERIALS AND MEASURING METHODS

Static friction tests of selected material combinations were carried out on the reciprocating friction test stand **[L. 20]** shown schematically in **Fig. 3**. The stand was modified to obtain a variable rate of increase in the force driving the relative motion in a friction pair. The modification consisted in installing a spring (with known characteristics) between the actuator forcing translational motion and the trolley (5) on which a counter-body was mounted. A steel sample in the form of a pin (1) was mounted in a stationary holder on a tilting arm (4), while the counter-body in the form of a plate (2) was mounted in a holder attached to the trolley (5) by means of rolling rollers (8). A weight (9) applied the load pressing the sample against the counter-body. Relative motion was forced by an electric actuator connected with the trolley (5) by the spring. A force sensor (6), connected by means of a beam (7) to the table (3) on which the sample was placed, registered friction force Ft. The force sensor was connected to a system recording the signal with a frequency of 100 Hz. The entire setup is mounted on a frame (10) made of aluminium profiles.

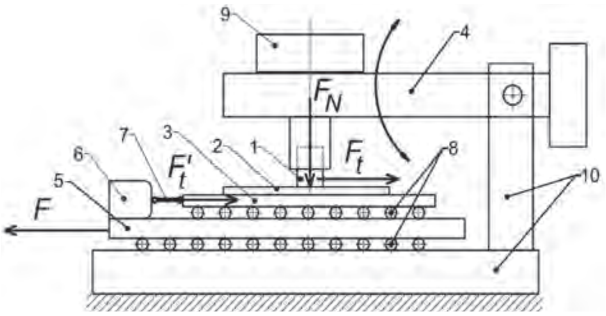

Fig. 3. Test stand for tribological investigations in reciprocating motion [L. 20]

Rys. 3. Stanowisko badawcze do badań tribologicznych w ruchu posuwisto-zwrotnym **[L. 20]**

Elastomeric and thermoplastic polymer materials were selected to sliding interaction with the steel pin. Elastomers can significantly deform elastically, which theoretically should be important when testing the friction coefficient at a variable gradient of the force driving the relative motion. The following materials were selected for the tests: thermoplastic elastomer – TPU polyurethane, silicone rubber (SI) and high-temperature thermoplastic – PSU polysulfone. The properties of the tested polymers are presented in **Table 1**. The tests were carried out in dry friction conditions. During the tests, the polymeric materials in the form of flat plates interacted with the flat surface of a cylindrical pin made of C45 steel with the hardness of 42 HRC and surface roughness Ra = 0.4–0.6 µm.

Table 1. Properties of tested polymer materials [L. 21]

Tabela 1. Własności badanych materiałów polimerowych **[L. 21]**

Polymer material	Modulus of elasticity E [MPa]	Hardness [ShD]	Density [Mg/m^3]
TPU (polyurethane)	200 ±100	28.7 ±1	1.25
PSU (polysulfone)	1700 ±200	80.4 ±2	1.42
SI (silicone rubber)	1400 ±300	15.1 ±1	1.17

The tests were carried out in the following friction conditions:

- Force rate: dF/dt = 0.1, 0.5, 1, 2, 5, 10, 15, 20 [N/s],
- Mean unit pressure: p = 0.5 [MPa],
- Time of standstill under load: tp = 1 [s],
- Ambient temperature: To = 22 [°C],
- Type of lubrication: technically dry.

RESULTS

The tested sliding pairs are listed in **Table 2** which also contains the mean values of the static friction coefficient and the confidence intervals. The mean values were calculated from a series of at least 50 measurements and the confidence intervals were determined for significance level α = 0.05. For comparison and easier analysis, the test results are presented in the form of graphs in **Fig. 4**.

The test results show that the static friction resistances are greater for higher velocities of the force increasing the relative motion in the sliding pair. This indicates that the viscoelastic properties of polymers significantly contribute to friction. Elastomeric materials are particularly sensitive to the rate at which the exciting force is increased.

The greatest effect of the rate of increase in the motion driving force was observed for the combination of TPU polyurethane with steel. For this sliding pair, the friction coefficient increased from 0.12 (for dF/dt = 0.1 N/s) to 0.51 (for dF/dt = 20 N/s). The smallest effect was observed for PSU polysulfone, which shows the highest value of the elasticity modulus among the tested materials. In the case of this polymer, the friction coefficient increased from 0.38 (for dF/dt = 0.1 N/s) to 0.46 (for dF/dt = 20 N/s).

Table 2. Static friction coefficient as function of rate of increase in force driving relative motion (dF/dt) for tested steel-polymer friction pairs

Tabela 2. Współczynnik tarcia statycznego badanych par trących stal–polimer w prędkości przyrostu siły wymuszającej ruch względny dF/dt

Counter-body material	Force rate dF/dt [N/s]							
	0.1	0.5	1	2	5	10	15	20
PSU	**038**±0.008	**0.37**±0.005	**0.37**±0.004	**0.36**±0.003	**0.39**±0.004	**0.44**±0.002	**0.43**±0.003	**0.46**±0.006
TPU	**0.12** ±0.011	**0.16** ±0.011	**0.19** ±0.008	**0.21**±0.006	**0.30**±0.007	**0.40** ±0.008	**0.41** ±0.006	**0.51** ±0.013
SI	**0.20**±0.007	**0.24** ±0.005	**0.26** ±0.006	**0.32**±0.006	**0.38** ±0.08	**0.47**±0.013	**0.48** ±0.007	**0.51** ±0.006

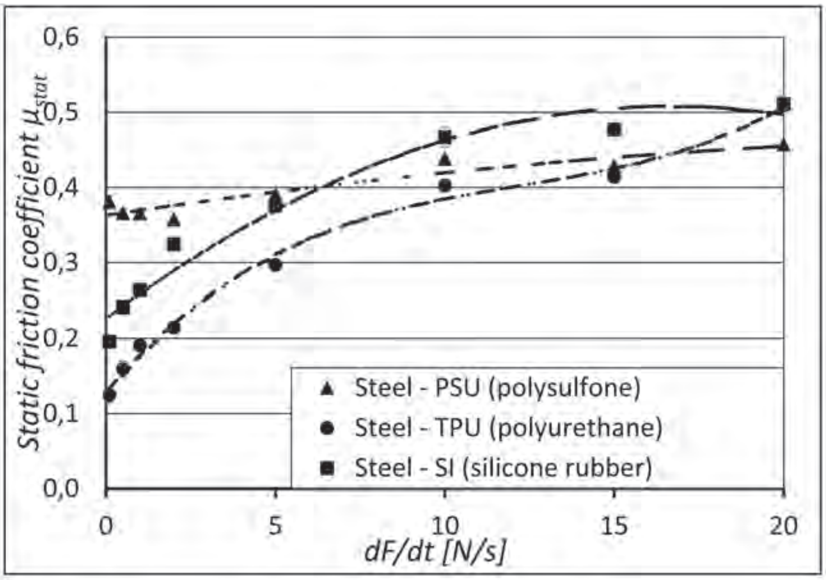

Fig. 4. Average values of static friction coefficient of tested pairs depending on motion driving force gradient (force rate)

Rys. 4. Średnie wartości współczynnika tarcia statycznego badanych skojarzeń w zależności od gradientu przyrostu siły powodującej ruch

CONCLUSIONS

The following conclusions can be drawn from the results of the tribological tests:

- Static friction resistance increases with the tangential force growth rate (dF/dt) for all the tested combinations. This is due to the fact that, with the increase in the deformation rate of the polymeric material, the share of the polymer deformation component in the total static friction resistance increases.
- The change in the value of the friction coefficient is correlated with the value of the material's modulus of elasticity. An inverse proportion between Young's modulus and the susceptibility to a change in frictional resistance is observed. The higher the value of the modulus, the smaller is the change in frictional resistance in relation to the rate of increase in force rate dF/dt [N/s].
- The steel-TPU pair is the most advantageous sliding combination, as it is characterized by the lowest static friction resistance ($\mu < 0.13$) for small increases in the motion driving force (dF/dt < 1 [N/s]). At the same time, this pair shows the highest susceptibility to changes in the growth rate of the tangential force which sets it in motion. Static friction resistance is highest at high rates of force growth.

In the case of the steel-PSU combination, only a slight change in the value of the static friction coefficient ($\mu = 0.38$–0.46) is noticeable. This is due to the fact that PSU is not an elastomeric material with a much higher modulus of elasticity. In this case, the share of the deformation component in the total static friction resistance is small.

In order to fully explain the results of the static friction tests, the measuring range must be extended to include higher tangential force growth rates; whereby, it will be possible to correlate the obtained characteristics with the mechanical characteristics of the tested materials. The scope of the research should also be extended to include other polymer materials characterized by different values of the modulus of elasticity in order to determine the influence of their mechanical properties on the dependence between the static friction coefficient and the rate of increase in the force driving the relative motion.

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