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# STATIC FRICTION OF REVERSE STEEL–ELASTOMER SLIDING PAIRS

# TARCIE STATYCZNE W ODWRÓCONYCH PARACH ŚLIZGOWYCH METAL–ELASTOMER

**Key words:** static friction, elastomers, revers frictional pair.

**Abstract**

Sliding cooperation of materials with different hardness (deformability), e.g., a polymeric material cooperating with metallic materials, occurs in machine elements in one of the following two variants: a conventional pair or a reverse pair.

In the case of the conventional sliding pair, the deformation area (contact area) of the sliding materials does not move on the surface of the polymer element during their cooperation. In the case of reverse pairs, the contact surface changes its position when moving on the surface of the polymer element. Depending on the variant of the sliding pair, the differences in the friction and wear process of polymer material can be observed.

Tribological investigations of chosen sliding pairs (elastomer on steel or steel on elastomer) in the static friction were carried out on the rig. The polymeric materials selected for the tests were thermoplastic elastomers TPU, PUR, and silicone rubber SI. These materials co-operated with C45 steel in the different contact pressures ($p = 0.1 – 0.26$ MPa) under dry friction or mixed lubrication conditions (hydraulic oil Hipol HLP-68). Based on the recorded value of the friction force Ft, the values of static coefficients of friction $\mu_{stat}$ were determined. The test results showed a significant influence of the variant of the combination of materials (metal-polymer or polymer-metal) on the value of the friction coefficient. In all tested pairs in which steel sample (pin) slid against elastomeric plates, the friction coefficient was higher than in the case when the elastomeric sample (pins) cooperated with steel counterfaces (plates). The main reason is the considerable value of the deformation component of the friction force. This is probably due to the displacement of the elastomer deformation area in its surface layer and energy dissipation as a result of stress-strain hysteresis in the elastomeric material, as in the case with reversed pairs.

**Słowa kluczowe:** tarcie statyczne, elastomery, odwrócone pary trące.

**Streszczenie**

Współpraca ślizgowa materiałów o różnych twardościach (odkształcalności), np. materiał polimerowy współpracujący z materiałem metalicznym, występuje w elementach maszyn w jednym z dwóch następujących wariantów: para prosta lub para odwrotna. Dla ślizgowej pary prostej obszar odkształcania (obszar styku) materiałów ślizgowych nie przemieszcza się na powierzchni elementu polimerowego podczas ich współpracy. W przypadku par odwrotnych powierzchnia styku zmienia swoje położenie podczas ruchu na powierzchni elementu polimerowego. W zależności od wariantu pary ślizgowej można zaobserwować różnice w procesie tarcia i zużycia materiału polimerowego.

Badania tribologiczne wybranych par ślizgowych (elastomer po stali lub stal po elastomerze) w tarciu statycznym przeprowadzono na tribotesterze do badań w ruchu posuwisto-zwrotnym. Materiałami polimerowymi wybranymi do badań były elastomery poliuretanowe TPU, PUR i guma silikonowa SI. Materiały te współpracowały ze stalą C45 o różnym nacisku jednostkowym ($p = 0{,}1–0{,}26$ MPa) w warunkach tarcia suchego lub mieszanego (olej hydrauliczny Hipol HLP-68). Na podstawie rejestrowanej wartości siły tarcia Ft na początku ruchu wyznaczono wartości statycznych współczynników tarcia $\mu_{stat}$.

Wyniki testu wykazały istotny wpływ wariantu kombinacji materiałów (metal-polimer, polimer-metal) na wartość współczynnika tarcia. We wszystkich testowanych kombinacjach materiałowych, w których próbka stalowa (sworzeń) ślizgała się po płytce elastomerowej, współczynnik tarcia był wyższy niż w sytuacji, gdy próbka elastomerowa współpracowała ze stalową płytą. Głównym powodem jest znaczna wartość składowej odkształceniowej siły tarcia. Jest to spowodowane prawdopodobnie przemieszczaniem się obszaru deformacji elastomeru w jego warstwie wierzchniej i rozpraszaniem energii w wyniku histerezy naprężeniowo-odkształceniowej w materiale elastomerowym, co ma miejsce w przypadku par odwróconych.

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## INTRODUCTION

Static friction plays an important role in the frictional resistance during the start-up of machines and devices. It also determines the resistance at the endpoints of movement in the case of reciprocating as well as swinging motion. In publications on static friction, the results of experimental investigations **[L. 1, 3, 8, 10]** or the results of numerical modelling **[L. 3, 4, 5, 7]** of the static friction of polymeric materials are presented. These studies usually concern elastomer materials or only thermoplastic materials cooperating with steel under dry friction conditions. In the majority of them, the authors draw attention to the significant share of adhesion in a static friction resistance.

The cooperation of materials with different hardness usually occurs in polymer-metal rubbing pairs. **Figure 1** presents two basic variants of sliding cooperation of materials with different elasticity [**L. 1, 2, 9**]:

- Conventional frictional pair (Variant I) – the deformation area (contact area) of the sliding materials does not move on the surface of the polymer element during their cooperation.
- Reverse frictional pair (Variant II) – the deformation area (contact area) of the sliding materials changes its position on the surface of the polymer element during cooperation.

Depending on the variant of the sliding pair, differences in the process of the friction and wear of the polymeric material can be observed **[L. 2–7, 9]**. This is mainly due to the method of a polymer film forming on the surface of the metallic element **[L. 7]**, and it is also due to the significant difference in deformability of polymeric and metallic materials. During sliding cooperation of this type of pairs, apart from the adhesive and mechanical interactions of the contacting surfaces, there is also frictional resistance associated with the deformation of the polymeric material **[L. 6, 9]**. Therefore, the choice of a sliding pair variant in tribological tests can affect the recorded results of friction resistance or tribological wear.

The aim of investigations presented in this paper was to determine the effect of contact pressure on a static friction coefficient, depending on the variant of the friction pair (conventional and reverse) of materials with different deformability, in dry or mixed conditions of friction.

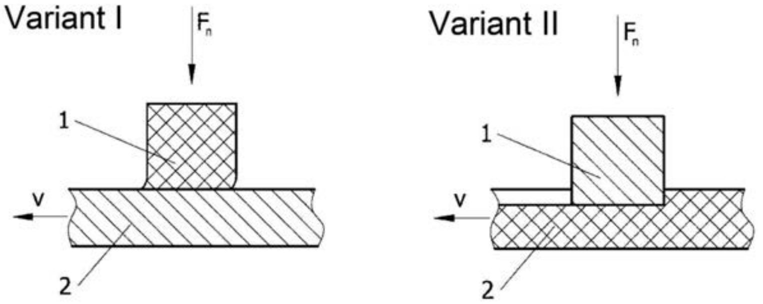

**Fig. 1. Variants of sliding pairs of materials with different deformability [L. 6, 9]: Variant I (conventional pair), Variant II (reverse pair) – metallic specimen(1), polymer counterface (2)**

Rys. 1. Warianty skojarzeń ślizgowych materiałów o różnej odkształcalności **[L. 6, 9]**: wariant I (para prosta), wariant II (para odwrócona) – próbka (1) stalowa, przeciwelement (2) polimerowy

## MATERIALS AND TEST METHODS

Static friction tests of selected combinations of materials were carried out on a test rig (Tribotester) designed for complex sliding and rolling movement **[L. 11]**. This stand has been adapted for static friction tests in reciprocating motion, and its scheme is shown in **Figure 2**. The sample in the form of a pin (1) was mounted in the holder, and the cooperating element in the form of a plate (2) was placed on the table (3). The table was fastened to the trolley (5) via rollers (8). The normal load was set with weights (9), which caused the sample to be pressed against the cooperating element. The reciprocating motion was enforced by an electric actuator connected by a rod to the trolley. The friction force $F_t$ was measured by a force sensor (6) connected to the table (3). The force sensor was connected to the signal recording device at a frequency of 100 Hz.

The tested materials were elastomers that are often used in technical seals. Therefore, the tests were carried out under technically dry friction conditions as well as in the presence of a lubricant (mixed friction).

The following elastomers were selected for the tests: TPU (thermoplastic polyurethane, hardness 65 ShA), PUR (polyurethane elastomer Vulkolland D15, hardness 70 ShA), and SI (silicone rubber, hardness 60 ShA). During the tests, these materials cooperated with elements made of C45 steel with a hardness of 42 HRC and the surface roughness Ra = 0.5 µm.

The tests were carried out under the following friction conditions:

- Average contact pressure p = 0.1 – 0.26 MPa,
- Dwell time under initial load tp = 2 s,
- Temperature of the environment To = 24ºC,
- Dry friction conditions or mixed friction conditions in the presence of the hydraulic oil *Hipol HLP 68*.

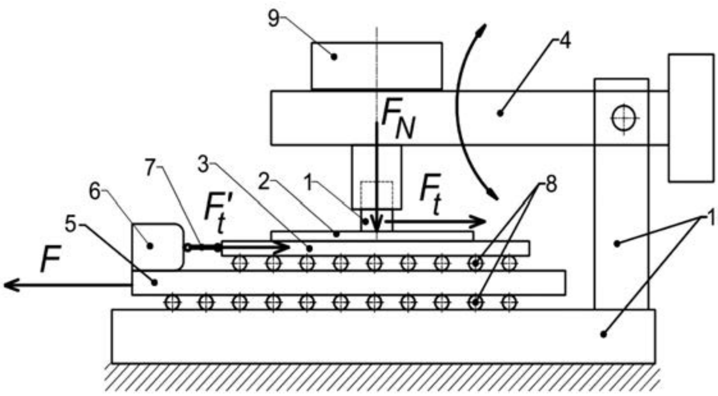

**Fig. 2. Tribotester for tribological tests in the reciprocating movement (description of elements in the text)**
Rys. 2. Stanowisko badawcze do badań tribologicznych w ruchu posuwisto-zwrotnym (opis elementów w tekście)

## TEST RESULTS

Variants of the tested sliding pairs are presented in **Tables 1** and **2**. The tables also include the results of tests that are the average values of static friction coefficient obtained from a series of at least 20 measurements. The confidence intervals specified at the significance level $\alpha = 0.05$ are given in the same tables. In order to compare the obtained results and make the analysis easier for conventional (polymer-steel) and reverse (steel-polymer) pairs, they are presented in the form of diagrams as shown in **Figures 3** and **4**.

The presented research results show that the static friction resistance in conventional pairs is smaller than the resistances in reverse pairs in both dry and mixed friction conditions. This indicates a significant contribution of the deformation component in frictional force in the case when the friction of a steel element takes place on materials with high deformability. It also follows that the adhesive component of frictional force does not constitute a significant value in the frictional resistance of the tested elastomeric materials for reverse pairs.

The lowest static friction coefficient in dry friction conditions was observed during the cooperation of conventional pairs TPU on steel (**Fig. 3a**). On the other hand, the smallest resistance in mixed friction conditions was observed for a pair SI on steel (**Fig. 4b**). The static friction coefficient for this pair was from 0.09 to 0.14, depending on the contact pressure.

The effect of contact pressure on the coefficient of static friction is varied. For steel-TPU and TPU-steel pairs (**Figs. 3a** and **4a**), the effect is negligible and the differences in the coefficient of friction were ±0.1. The highest variation in the coefficient of friction was observed for the steel-PUR reverse pair operating under dry friction conditions (**Fig. 3c**). With the increase in the contact pressure, the coefficient of static friction decreased from 0.85 (for p = 0.1 MPa) to 0.38 (for p = 0.26 MPa).

**Table 1. Effect of contact pressure *p* on the coefficient of static friction for reverse sliding pairs (steel on polymer)**
Tabela 1. Wpływ nacisku jednostkowego *p* na współczynnik tarcia statycznego ślizgowych par odwróconych (stal–polimer)

| Material of counterface | Contact pressure p [MPa] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.10 | 0.13 | 0.15 | 0.18 | 0.21 | 0.23 | 0.26 |
| Dry friction conditions | | | | | | | |
| TPU | **0.58** ±0.044 | **0.69** ±0.039 | **0.69** ±0.030 | **0.70** ±0.033 | **0.72** ±0.028 | **0.75** ±0.026 | **0.72** ±0.023 |
| SI | **0.60** ±0.014 | **0.72** ±0.012 | **0.73** ±0.015 | **0.73** ±0.016 | **0.69** ±0.015 | **0.66** ±0.016 | **0.63** ±0.014 |
| PUR | **0.85** ±0.070 | **0.80** ±0.071 | **0.65** ±0.062 | **0.69** ±0.052 | **0.61** ±0.038 | **0.57** ±0.021 | **0.38** ±0.012 |
| Mixed friction conditions | | | | | | | |
| TPU | **0.71** ±0.046 | **0.72** ±0.027 | **0.77** ±0.009 | **0.72** ±0.015 | **0.72** ±0.015 | **0.69** ±0.010 | **0.67** ±0.012 |
| SI | **0.36** ±0.014 | **0.36** ±0.017 | **0.36** ±0.004 | **0.31** ±0.014 | **0.34** ±0.014 | **0.32** ±0.006 | **0.35** ±0.009 |
| PUR | **0.47** ±0.035 | **0.66** ±0.054 | **0.67** ±0.049 | **0.66** ±0.052 | **0.69** ±0.050 | **0.70** ±0.044 | **0.76** ±0.047 |

**Table 2. Effect of contact pressure *p* on the coefficient of static friction for conventional sliding pairs (polymer on steel)**
Tabela 2. Wpływ nacisku jednostkowego *p* na współczynnik tarcia statycznego ślizgowych par prostych (polimer–stal)

| Material of specimen | Contact pressure p [MPa] | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.10 | 0.13 | 0.15 | 0.18 | 0.21 | 0.23 | 0.26 |
| Dry friction conditions | | | | | | | |
| TPU | **0.34** ±0.007 | **0.35** ±0.005 | **0.36** ±0.004 | **0.35** ±0.004 | **0.32** ±0.003 | **0.34** ±0.004 | **0.26** ±0.005 |
| SI | **0.55** ±0.025 | **0.72** ±0.025 | **0.60** ±0.015 | **0.52** ±0.012 | **0.51** ±0.010 | **0.50** ±0.009 | **0.46** ±0.008 |
| PUR | **0.43** ±0.006 | **0.49** ±0.005 | **0.47** ±0.004 | **0.48** ±0.004 | **0.39** ±0.003 | **0.40** ±0.003 | **0.41** ±0.003 |
| Mixed friction conditions | | | | | | | |
| TPU | **0.35** ±0.004 | **0.40** ±0.002 | **0.39** ±0.001 | **0.37** ±0.002 | **0.34** ±0.002 | **0.37** ±0.003 | **0.37** ±0.002 |
| SI | **0.13** ±0.006 | **0.14** ±0.002 | **0.14**±0.002 | **0.11** ±0.003 | **0.09** ±0.004 | **0.12** ±0.005 | **0.12** ±0.009 |
| PUR | **0.32** ±0.006 | **0.37** ±0.007 | **0.38** ±0.006 | **0.30** ±0.004 | **0.34** ±0.007 | **0.34** ±0.006 | **0.35** ±0.005 |

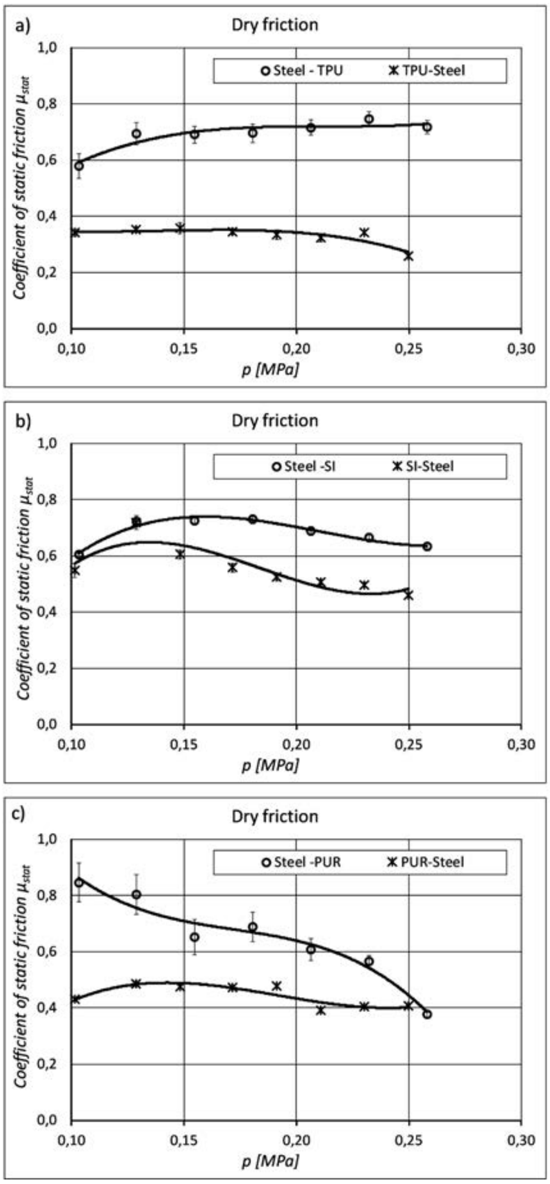

**Fig. 3. Effect of contact pressure p on the coefficient of static friction for conventional (polymer on steel) and reverse (steel on polymer) sliding pairs in dry friction conditions**
Rys. 3. Wpływ nacisku jednostkowego p na współczynnik tarcia statycznego par prostych (polimer po stali) i odwróconych (stal po polimerze) przy tarciu suchym

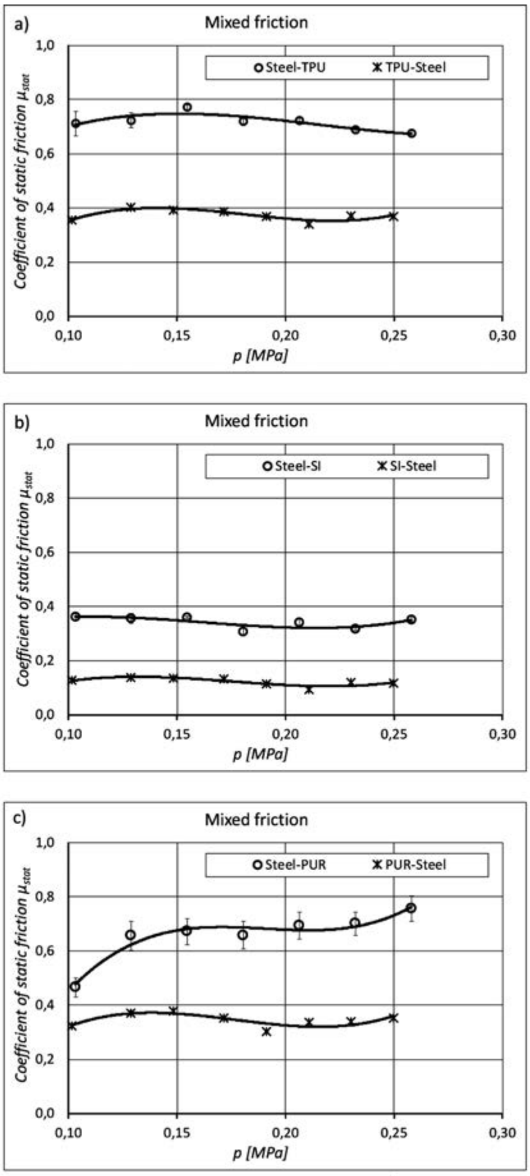

**Fig. 4. Effect of contact pressure p on the coefficient of static friction for conventional (polymer on steel) and reverse (steel on polymer) sliding pairs in mixed friction conditions**
Rys. 4. Wpływ nacisku jednostkowego p na współczynnik tarcia statycznego par prostych (polimer po stali) i odwróconych (stal po polimerze) przy tarciu mieszanym

The reduction of the friction coefficient value was also observed for the pair in which the SI elastomer cooperated with the steel under dry friction conditions (**Fig. 3b**). Changes in friction coefficient concerned both conventional and reverse pairs. In the case of this sliding pair, as the contact pressure was increased, the coefficient of friction initially increased, but at the pressure above 0.15 – 0.18 MPa, its value decreased.

The contact pressure only slightly affected the static friction coefficient of the tested pairs in the case of mixed friction. The exception was the reverse pair steel-PUR, where an increase of the friction coefficient with increasing contact pressure was observed (**Fig. 4c**).

The presented research results show that the deformation of the cooperating elements can also contribute to uneven pressure distribution occurring between the sliding parts. This can result in differences in the recorded frictional resistance values, especially in mixed friction conditions.

A significant difference in the deformability of sliding elements affects the characteristics of friction resistance. A detailed explanation of the effect of sliding elements deformability on static friction resistance would require additional tribological tests.

## SUMMARY AND CONCLUSIONS

The results obtained during tribological tests made it possible to formulate the following conclusions and comments:

- Static friction resistance in conventional pairs is smaller than resistances in reverse pairs in both dry and mixed friction conditions. In this case, the deformation component determines the total frictional resistance. This is due to the considerable deformability of the elastomeric element and energy dissipation as a result of stress-strain hysteresis of elastomeric materials. The deformed material area in the elastomer practically does not move in conventional pairs; therefore, the deformation component of friction is smaller than in reverse pairs.
- The most advantageous sliding pair due to the lowest resistance of static friction ($\mu_{stat} < 0.36$) under dry friction conditions was the conventional pair TPU on steel, while under mixed friction conditions, the smallest static friction coefficient ($\mu_{stat} < 0.14$) occurred for the SI-steel pair. It is worth noting that, in the case of these materials, the average value of the coefficient of friction only slightly changed with the change of contact pressure.
- Test results were characterized by a large dispersion and average values of the coefficient of friction that varied with a change in contact pressure in the case of reverse pairs (steel-elastomer). This probably resulted from the different surface structure of elastomeric materials at the area of contact with a metal element in subsequent measurements.
- A detailed explanation of the obtained results of static friction tests requires additional investigation of adhesive interactions between tested materials in both dry friction and in a presence of lubricants.

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