**Maciej KUJAWA*, Aneta NIEMIEC*, Wojciech WIELEBA***

# THE INFLUENCE OF DEFORMATION OF SELECTED THERMOPLASTICS ON THE FRICTION WITH STEEL

## WPŁYW ODKSZTAŁCENIA WYBRANYCH POLIMERÓW TERMOPLASTYCZNYCH NA TARCIE PO STALI

**Key words:**

POM, PTFE, PE-HD, PMMA, deformation, change in the friction coefficient, change of hardness

**Słowa kluczowe:**

POM, PTFE, PE-HD, PMMA, odkształcenie, zmiana współczynnika tarcia, zmiana twardości

**Abstract**

Friction and wear of materials with additional deformation or stress is not a broadly described case. However, scientific publications considering this issue point out that additional deformation and stress ought to be taken into account during wear and friction analysis. In this article, the influence of strain in thermoplastics (POM, PTFE, PE-HD, PMMA) over the friction coefficient is

* Wroclaw University of Technology, Faculty of Mechanical Engineering, Department of Machine Desing and Tribology, ul. I. Łukasiewicza 7/9, 50-371 Wrocław, Poland, e-mails: maciej.kujawa@pwr.edu.pl, tel. +48 71-320-27-75; aneta.niemiec@pwr.edu.pl, tel. +48 71-320-40-31; wojciech.wieleba@pwr.edu.pl, tel. +48 71-320-27-74.

described. Materials were deformed under tensile stress and examined after 24 hours. For specimens in which plastic strain was maintained, the decline of hardness (PE-HD: approximately 70% decrease, PTFE: approximately 40% decrease) and the reduction of the coefficient of kinetic friction (both PTFE and PE-HD: about 20% decrease) were observed. POM returned to its pre-deformed shape and PMMA was deformed without reaching its elastic limit. In these cases, only small changes in hardness (POM: approximately 10% decrease, PMMA: approximately 6% increase) and friction coefficients (maximum 4% change) occurred.

## INTRODUCTION

Parts in a tribological pair could be loaded not only by fiction force but also by other forces. External forces may affect a component, e.g., forces applied during assembly. A bushing pressed into a hole is compressed and deformed. Dynamic seals made of polytetrafluoroethylene (PTFE) are deformed near the contact area between them and a housing as well as near the contact area between them and a shaft. In this case, friction occurs between the deformed (tension and bending) polymer element and the slightly deformed metal element. Similar phenomena occur in elastomeric dynamic seals **[L. 1]**.

Strain and stress are analysed mainly as a result of material elements sliding against each other **[L. 2]**. However, research on the friction and wear of materials under external loads are also conducted. Some works are concerned with metallic materials and focuses on a specific field, that is, deep-sea exploitation. Under a few kilometres of seawater, the most significant load is high hydrostatic pressure. An analysis **[L. 3]** focuses on micro-cracks. Micro-cracks allow seawater to penetrate material and cause an acceleration of the generation of wear particles. Nevertheless, the findings reported in the article **[L. 4]** show that material becomes more ductile under hydrostatic pressure and wear is increased. Apart from research conducted in deep-sea environment, more general studies were carried out. In the case of aluminium alloy Al 7175 the influence of tension and compression on wear was assessed **[L. 5]**.

Deformed polymer materials have been mentioned in a few studies **[L. 6, 7]**. The findings of those studies prove that the friction coefficient between polymer material after deformation under tension and steel is lower than in the case of undeformed polymer. Deformed specimens made of polyamide 6 (strain 300%) have an orderly microstructure and, as a result, hardness was increased and the friction coefficient was lower.

It is noticeable that published papers show a consistency in the view on deformation's influence. Strain and stress ought to be taken into account during wear and friction coefficient analysis. This kind of conclusion and the lack of consideration in literature have motivated the authors of this paper to investigate

the influence of deformation on the friction coefficient between polymer and steel.

## MATERIALS AND MEASURING METHODS

Two states of polymer materials are investigated during the research: undeformed and deformed. Microhardness and friction coefficient are tested. Specimens are deformed under tension at room temperature $T_0 = 22°C$ using a tensile testing machine at a speed 10 mm/min. Their dimensions (thickness 4 mm, width 10 mm) are identical to the dimensions of specimens used in the standard test method for tensile properties of plastics. They are cut out of sheets made of polymers: high-density polyethylene (PE-HD), polytetrafluoroethylene (PTFE), poly(methyl methacrylate) (PMMA), and polyoxymethylene (POM). Rheological properties of those polymer materials vary.

Specimens were deformed to high plastic strain; however, fracture was impermissible. Specimens were removed from tensile testing machine directly after obtaining the desired strain and left under no load for 24 hours. After this time, hardness measurements were carried out, and the friction coefficient was examined (friction parameters: pressure, sliding velocity, ambient temperature etc. remained steady). Deformed PE-HD ($\varepsilon = 300\%$) obtained $\varepsilon = 500\%$ in the necking region. After 24 hours, a return to original length was not observed and strain retained its value. Deformed PTFE ($\varepsilon = 300\%$) reduced its strain after 24 hours. Strain remained at $\varepsilon = 70\%$. Deformed POM returned to its original length after 24 hours. PMMA was deformed ($\varepsilon = 3\%$) up to the yield point, because it is in the brittle state at ambient temperature $T_0 = 22°C$.

The Vickers hardness test was performed using a Schimadzu HMV micro Vickers hardness tester. Five measurements were conducted, and then the mean and expanded uncertainties were calculated. A 980.7 mN load was applied for 20 seconds.

Measurements of the friction coefficient were carried out for reciprocating motion using pin-on-plate equipment described in the paper **[L. 8]**. **Figure 1** shows the scheme of the apparatus. The bed with the specimen is moved by an electric actuator. A counter specimen is able to move along the vertical direction, and it is loaded with weight plates. The force sensor records the value of the friction force. Logged friction force values were used to calculate the friction coefficient, its mean value, and expanded uncertainty. The investigated tribological pair consisted of a polymer plate and 3 mm diameter pin made of steel (A1). Pressure was 3.0 MPa. However, during PMMA examination, pressure was reduced to 2.25 MPa in order not to exceed permissible values of friction force for the force sensor.

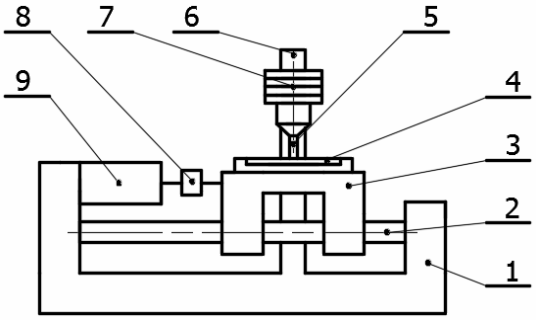


**Fig. 1. The scheme of the pin-on-plate device used in the current research (1 – the base, 2 – the way, 3 – the bed, 4 – a specimen, 5 – a counter specimen, 6 – the way of counter specimen fastening, 7 – weight plates, 8 – the friction force sensor, 9 – the electric actuator).**

Rys. 1. Schemat stanowiska typu *pin-on-plate* użytego w opisanych badaniach (1 – korpus, 2 – prowadnica, 3 – łoże, 4 – próbka, 5 – przeciwpróbka, 6 – prowadnica mocowania przeciwpróbki, 7 – obciążniki, 8 – czujnik siły tarcia, 9 – siłownik elektryczny)

The stepper motor mounted in the electric actuator is controlled by a PLC. As a result, the machine is able to perform autonomously. It consists of 30 strokes under a velocity of 20 mm/s, a 5-second break, and 20 strokes under a velocity of 10 mm/s. The pause helps to separate data during processing. Before the measurement of friction coefficient, a break-in procedure was carried out. It lasts 3 minutes and consists of 150 15 mm displacements. Variations in friction coefficient values, depending on sliding velocity, were insignificant. Thus, further analysis includes only measurements under a velocity of 10 mm/s.

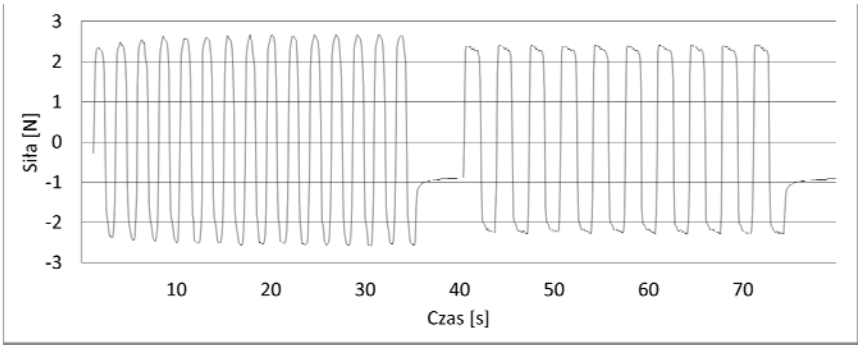


**Fig. 2. An example of PTFE examination presenting a program consisting of 30 strokes under a velocity of 20 mm/s, a 5-second break, and 20 strokes under a velocity of 10 mm/s**

Rys. 2. Przykładowy pomiar próbki PTFE prezentujący program składający się z 30 suwów o prędkości 20 mm/s, 5-sekundowej przerwy i 20 suwów o prędkości 10 mm/s

## RESULTS AND DISCUSSION

As for deformed polymers, hardness declines **(Table 1)**. This phenomenon occurred in the most significant way in the case of PE-HD. The specimen made of PE-HD was the most deformed. PE-HD hardness decreased by almost 70%. As far as PTFE is concerned, hardness decreased by almost 40% after partially returning to its original length. With regard to POM, a decline in hardness also occurred, however, to a lesser degree (roughly 10%). In the case of PMMA, a small increase in hardness was observed (more than 6%). The difference between deformed polymer hardness and undeformed polymer hardness may indicate changes in the super-molecular structure.

**Table 1. Hardness of not deformed and deformed materials and confidence intervals ($1 - \alpha = 0.95$)**

Tabela 1. Twardość materiałów polimerowych przed i po odkształceniu oraz przedziały ufności jej wartości ($1 - \alpha = 0{,}95$)

| Material | PE-HD | PTFE | POM | PMMA |
|---|---|---|---|---|
| Before deformation under tension | | | | |
| Hardness (HV 0.1) | 10.4±1.4 | 3.1±0.1 | 18.7±0.5 | 18.6±0.6 |
| After deformation under tension and being under no load for 24 hours | | | | |
| Hardness (HV 0.1) | 3.3±0.1 | 1.9±0.1 | 16.8±0.6 | 19.8±0.3 |
| Strain (ε) | 500% | 70% | 0% | 0% |

As for the tribological pair of deformed PE-HD–steel, a lower friction coefficient was observed than for pair of undeformed PE-HD–steel **(Table 2)**. The friction coefficient decreased roughly by 23%. As far as the tribological pair of deformed PTFE–steel is concerned, a lower friction coefficient was observed than for pair of undeformed PTFE–steel. The friction coefficient decreased by about 27%. POM, after deformation, returned to its original length. In the case of the tribological pair of deformed POM–steel, no significant change was observed in comparison with the pair of undeformed POM–steel. The friction coefficient changed only by about 4%. PMMA was deformed up to the yield point. With regard to the tribological pair of deformed PMMA–steel, no significant change was observed in comparison with the pair of undeformed PMMA–steel. The friction coefficient changed only by about 3%.

**Table 2. Friction coefficient and confidence intervals (1 – α = 0.95) for the pairs polymer–steel (A1) in the case of not deformed and deformed polymer (sliding velocity v = 10 mm/s)**

Tabela 2. Współczynnik tarcia oraz przedziały ufności jego wartości (1 – α = 0,95) dla skojarzeń polimer–stal (A1) przed i po odkształceniu polimeru (prędkość ślizgania v = 10 mm/s)

| Material | PE-HD | PTFE | POM | PMMA |
|---|---|---|---|---|
| Before deformation under tension | | | | |
| Friction coefficient (μ) | 0.291±0.002 | 0.108±0.002 | 0.209±0.002 | 0.523±0.004 |
| After deformation under tension and being under no load for 24 hours | | | | |
| Friction coefficient (μ) | 0.224±0.002 | 0.079±0.002 | 0.218±0.003 | 0.509±0.003 |
| Strain (ε) | 500% | 70% | 0% | 0% |
| A return to original length | no | partial | yes | yes |

## SUMMARY AND CONCLUSIONS

Permanent deformation in polymers caused a decrease (over 20%) in the friction coefficient in the tribological pair polymer–steel (A1) in comparison with pair of undeformed polymer–steel. This phenomenon was observed in the case of PE-HD and PTFE. Moreover, a decrease of these polymers hardness was reported – almost 70% in the case of PTFE and about 40% in the case of PE-HD. POM after deformation (ε = 25%) and left under no load for 24 hours returned to its original length (ε = 0%). With regard to the tribological pair of deformed POM–steel, no significant change was observed in comparison with pair of undeformed POM–steel. Only a slight change in hardness was observed (roughly 10%). As far as PMMA is concerned, when deformed up to its yield point, hardness changed less in comparison with POM (a slight increase to around 6%). No significant change in the friction coefficient was reported.

The change in the friction coefficient for the pair polymer–steel was observed, however, only in the case of permanent deformed polymers (PE-HD and PTFE). Deformation and a return to original length (in the case of POM) or deformation only up to yield point (in the case of PMMA) did not cause any changes in the investigated properties. These phenomena may be explained by the fact that permanent deformation causes modifications in the super-molecular structure and probably a change in the degree of crystallinity. Additional examination of polymer structures might resolve doubts. Such an examination is planned by the authors in the near future.

Further investigation of this phenomenon ought to include materials with a tendency to return to their original length, e.g. POM. It would be required to prevent those materials from returning to their original length after deformation. Subsequently, measurement ought to be conducted during a maintenance of

deformation. Pin-on-plate equipment ought to be modified to facilitate such an investigation.

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**Streszczenie**

**Tarcie i zużycie materiałów odkształconych lub naprężonych w wyniku działania sił niepochodzących od współpracy w skojarzeniu nie jest obszernie opisanym zagadnieniem. Jednakże publikacje traktujące o tej tematyce są zgodne w jednym: stan odkształcenia i naprężenia w materiale powinien być brany pod uwagę przy analizie zjawiska tarcia i zużycia. W artykule opisano wpływ odkształcenia polimerów termoplastycznych POM, PTFE, PE-HD i PMMA na współczynnik tarcia polimer-stal. Materiały rozciągnięto i pozostawiono w stanie nienaprężonym na 24 godziny. W próbkach, w których wystąpiło i utrzymało się trwałe odkształcenie plastyczne zaobserwowano zmniejszenie twardości (dla PE-HD o około 70%, dla PTFE o około 40%) i redukcję współczynnika tarcia kinetycznego (dla obu polimerów o ponad 20%). POM, który całkowicie powrócił do pierwotnej postaci i PMMA rozciągnięty tylko w zakresie sprężystym wykazały niewielkie zmiany odnośnie do twardości (POM spadek o około 10% i PMMA wzrost o około 6%) i współczynnika tarcia (zmiana o maksymalnie 4%).**