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THE INFLUENCE OF UNIAXIAL COMPRESSION ON THE FRICTION COEFFICIENT (POLYMER–STEEL PAIR), WEAR, AND HARDNESS IN SELECTED THERMOPLASTICS

WPŁYW JEDNOOSIOWEGO ŚCISKANIA WYBRANYCH POLIMERÓW TERMOPLASTYCZNYCH NA WSPÓŁCZYNNIK TARCIA PO STALI, ZUŻYWANIE I TWARDOŚĆ

Key words: strain, stress, deformation, PTFE, PA6, PE-HD.

Abstract Plastic plain bearings are deformed during assembly. According to one of the leading manufacturers of plastic sliding elements, the bushing's internal diameter may be reduced by up to 2.5%. Moreover, plastic sliding elements are increasingly used in harsh conditions (e.g., under high pressure). However, there are no papers that describe the influence of deformation under compression on the tribological properties of plastics. Specimens made of PTFE, PA6, and PE-HD were deformed while conducting the current research, and this deformation was maintained during cooperation with steel. The results of microhardness, wear, and the coefficient of friction tests were compared to data gathered during tests of non-deformed specimens. During deformation under compression ($\varepsilon \approx 6\%$), microhardness lowered by up to 30% (PTFE). A significant reduction of hardness (by up to 15%) was observed when strain was only 2%, and up to this value of strain, there is mainly elastic deformation in the polymer. Changes of the coefficient of friction values were insignificant. In terms of PTFE and PE-HD, during deformation under compression up to $\varepsilon \approx 6\%$, the block scar volumes were 20% and 40% larger, respectively, than the non-deformed form of specimens. In terms of PA6, the change in block scar volume was insignificant. It may seem that tension and compression ought to cause totally different effects. However, the comparison of the current results and the results described in the previous paper exposes that these two different processes led to the same effects – reducing hardness and increasing wear. Deformation of plastic sliding components as an effect of assembly appears to be minor; however, it affects polymer microhardness and wear resistance.

Słowa kluczowe: odkształcenie, naprężenie, PTFE, PA6, PE-HD.

Streszczenie Polimerowe elementy ślizgowe podczas montażu w urządzeniu ulegają odkształceniu. Jeden z czołowych producentów elementów ślizgowych z tworzyw sztucznych podaje, że po montażu średnica wewnętrzna tulei może zmniejszyć się aż do 2,5%. Ponadto tego typu elementy są stosowane w coraz bardziej wymagającym otoczeniu (np. przy znacznym ciśnieniu), a w literaturze nie można znaleźć informacji na temat wpływu ściskania na właściwości tribologiczne. W opisanych badaniach utrzymywano w ściśnięciu próbki wykonane z PTFE, PA6 i PE-HD i w takim stanie poddano je współpracy ze stalą. Wyniki dotyczące współczynnika tarcia, zużywania i mikrotwardości porównywano z wartościami uzyskanymi dla nieodkształconych materiałów. Po ściśnięciu materiałów do $\varepsilon \approx 6\%$ mikrotwardość zmniejszyła się nawet o 30% (w przypadku PTFE). Znaczące zmiany mikrotwardości (do 15% różnicy) pojawiły się już przy odkształceniu do 2%, czyli w zakresie, gdzie dominują w polimerze odkształcenia odwracalne (sprężyste). Nie zaobserwowano znaczących zmian współczynnika tarcia. Dla PTFE i PE-HD po odkształceniu do $\varepsilon \approx 6\%$ objętość usuwanego podczas współpracy materiału zwiększyła się odpowiednio o 20% i 40%. W przypadku PA6 nie odnotowano znaczących zmian. Wydawać by się mogło, że ściskanie i rozciąganie powinny powodować przeciwstawne skutki. Porównując jednak uzyskane wyniki do tych z poprzednich badań, okazuje się, że prowadzą one do tego samego – zmniejszenia twardości i zwiększenia zużywania. Pomimo że odkształcenia wprowadzane do polimeru podczas montażu tudzież pracy elementu ślizgowego wydają się niewielkie, to mają one wpływ na twardość materiału i odporność na zużywanie.

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INTRODUCTION

Deformation as an approach to achieve better properties of polymers is mainly used during the manufacture of fibres **[L. 1]**. Strengthening of polymer is an effect of structure orientation. Polymer chains which are not arranged in order during deformation under tension align in parallel in the direction of deformation. As an effect of this phenomenon, strength of the polymer is increased, since force is transferred by strong covalent bonds, and not by weaker secondary bonds.

The structure orientation phenomenon (extremely important in fibres manufacturing) appeared to be a chance to improve the polymer's tribological properties. Therefore, the influence of structure orientation on tribological properties was previously closely examined. **[L. 2]**. To achieve structure orientation, the polymer ought to be deformed to a large strain. The author of this publication has proved that deformation under tension influences microhardness and wear **[L. 3]**. Moreover, this phenomenon was observed when strain was minor (up to a few percent) **[L. 4]**.

When analysing the opposite process (compression), the influence of deformation under compression on tribological properties of polymers has not been described in the literature. Plastic sliding elements have a few advantages that encourage engineers to apply them in a vast number of new devices and machines. They are able to work without lubrication; therefore, they are ecological and maintenance-free. Plastic sliding elements are progressively applied in places where they are highly loaded. For instance, they work under pressure in fluid power elements like pumps, valves, and hydraulic cylinders **[L. 5]**. Furthermore, they are applied as plain bearings in submarine rudders and propellers. It is worth mentioning that the dimension of the bushing housing is selected so that the bushing is fixed. According to one of the leading manufacturers of plastic sliding elements, the bushing's internal diameter may be reduced by up to 2.5% after assembly into housing.

The author of this paper decided to conduct research about the influence of deformation under compression on selected properties of polymers because of three reasons. Firstly, the results considering deformation under tension were encouraging. Secondly, there have been no papers considering the influence of deformation under compression on selected properties of polymers. Finally, it is evident that polymer sliding components cooperate with other elements when they are deformed.

MATERIALS AND MEASURING METHODS

Two states of polymer materials were investigated during the research: non-deformed and deformed. Microhardness, wear, and the friction coefficient were tested. Specimens were deformed under tension at room temperature (T_0 = 22°C). The dimensions of specimens were chosen according to ISO international standard considering determination of compressive properties **[L. 7]**. The specimens were cuboids with a length and width of 10 mm, and the specimens were cut out of sheets. They were made of three polymers: high-density polyethylene (PE-HD), polytetrafluoroethylene (PTFE), and polyamide 6 (PA6). Each of the chosen polymers is used in plastic sliding elements. However, each of the described polymers has different rheological and mechanical properties.

The specimens were compressed using a vice **(Fig. 1)**. The movement of jaws was controlled manually. There were two stages of measurements. The first one concerned strain up to 2% ($\varepsilon \leq 2\%$), and the second one concerned strain $2\% \leq \varepsilon \leq 6\%$. When strain is up to about 2% in the polymer, there is mainly an elastic deformation. When strain is higher than about 2% in the polymer, there is mainly a plastic deformation. The maximum strain was 6%, since, when the strain value was higher, an undulation pattern on the specimens' surface was observed. The actual value of strain was obtained using the optical method. Two indentations in non-deformed polymer were conducted. The distance between them was measured after each deformation, and actual strain was calculated. Due to rheological phenomena, measurements were conducted directly after obtaining the desired strain.

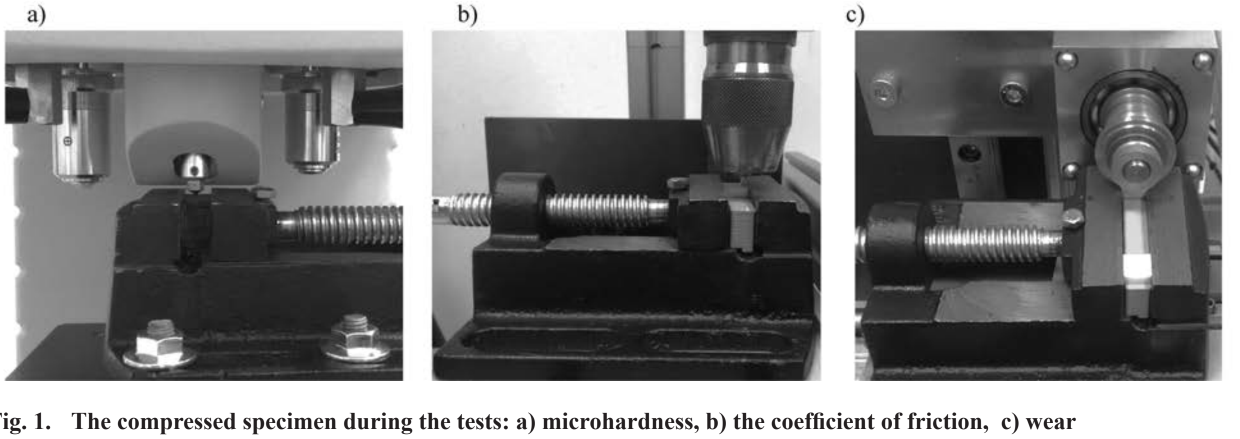

Fig. 1. The compressed specimen during the tests: a) microhardness, b) the coefficient of friction, c) wear

Rys. 1. Próbka utrzymywana w ściśnięciu podczas badań: a) mikrotwardości, b) współczynnika tarcia, c) zużywania

Microhardness

During the research, hardness was measured, since it is a significant parameter considering materials cooperation. Furthermore, the change in hardness is related to the change in material's microstructure. Therefore, the measurements of hardness may be useful in selecting potentially interesting areas for a prospective research.

Plastic sliding elements that are applied in devices and machines usually cooperate with metal components. Therefore, there is cooperation between two materials that differ considerably in terms of hardness. A polymer surface is much more deformed than a metal surface. Consequently, the author decided to measure microhardness instead of nanohardness. Measuring microhardness allows one to penetrate material deeper and gather information about hardness at greater depths.

In terms of plastics, hardness tests methods are base on measurements of indentation depth (for instance usage of shore durometer) **[L. 8]**. It is an effect of visco-elastic properties of polymers, since, after removing the indenter, the shape of the indentation changes. However, in terms of the described research, the author decided to use the Knopp method which is based on the determination of the size of the indentation. The reason to use Knopp method is the accurate shape of the indenter used in this method. The value of the indenter length is 7 times larger than width. This allows one to measure microhardness in different directions. Since the research is to compare two states of material (non-deformed and deformed), the indentation shape change was irrelevant after removing the indenter.

The hardness test was performed using a Schimadzu HMV microhardness tester. The directions of hardness measurements were parallel to the direction of compressive force. The indenter was loaded (98.07 mN) for 5 seconds. Since the length of indentation was measured, and the angle of indenter tip was known, the depth of indentation might be calculated. The calculated indentation depth was between 3.75 µm (in terms of the hardest material – PA6) and 9 µm (in terms of the softest material – PTFE). In terms of each material, 3 samples were tested. In terms of each strain value, indentations were made in 3 different areas of the surface of the sample.

The coefficient of friction

Measurement of the coefficient of friction and wear required special conditions. The tribotester ought to have provided enough space for the vice that maintained specimen compression. Therefore, the author decided to use the pin-on-plate tribotester described in the paper **[L. 9]**. **Figure 2** shows the picture and the scheme of the apparatus. The bed with the specimen is moved by an electric actuator. A counter specimen is able to move along in the vertical direction, and it is loaded with weight plates. The force sensor records the value of the friction force. The registered friction force value was used to calculate the friction coefficient, its mean value, and expanded uncertainty. The stepper motor mounted in the electric actuator is controlled by a PLC. As a result, the machine is able to perform its own demanded programme. It consists of 50 strokes under a velocity of 10 mm/s. The investigated tribological pair consisted of a polymer plate and steel pin with a diameter of 2 mm. Contact pressure was 3.0 MPa.

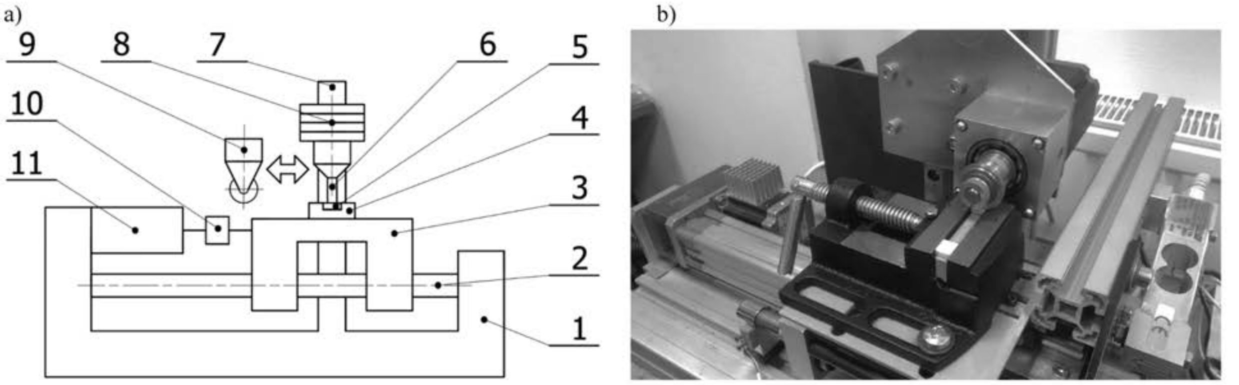

Fig. 2. a) the scheme of the pin-on-plate device used in the current research: 1 – the base, 2 – the way, 3 – the bed, 4 – a specimen, 5 – the specimen holder, 6 – a counter specimen, 7 – the way of counter specimen fastening, 8 – weight plates, 9 – a roller driven by stepper motor that may be assembled as an alternative for (6) to perform wear test, 10 – the friction force sensor, 11 – the electric actuator; b) the photography of the device (configuration that allows to perform wear test)

Rys. 2. a) schemat stanowiska typu pin-on-plate użytego w opisanych badaniach: 1 – korpus, 2 – prowadnica, 3 – łoże, 4 – imadło, 5 – próbka, 6 – przeciwpróbka, 7 – prowadnica mocowania przeciwpróbki, 8 – obciążniki, 9 – silnik krokowy z rolką montowany (zamiennie z przeciwpróbką (6) podczas badań zużywania), 10 – czujnik siły tarcia, 11 – siłownik elektryczny); b) fotografia stanowiska w wersji wykorzystanej do badań zużywania

During the first stage of measurements, the specimen was placed between vice jaws, and the test was carried out with a non-deformed specimen. During the second stage, the specimen was deformed to ε ≤ 2% and the precise value of strain was obtained using the microscope. Measurement of the deformed specimen was carried out beside the place of the measurement of the non-deformed specimen. This procedure was repeated when the specimen was deformed to 2% ≤ ε ≤ 6%. Due to this process, the specimen was examined in deformed and non-deformed states, and it was mounted only one time. Reassembly of the specimen was not needed, and this assured better reliability of measurements. Gathered data allowed conducting a comparison of non-deformed and deformed states. The results are presented as a percentile decrease/increase

Wear

In terms of the described tribotester, the holder of the counter specimen may be replaced by the ring driven by a stepper motor. This option was used during wear tests. The wear test method was similar to the block-on-ring wear test. The steel ring was rotating and cooperating with the plastic plate. The dimensions of groove that appear after cooperation were used to assess wear.

The ring was 3 mm thick, and its diameter was 30 mm. In terms of PE-HD, the load was 5 kg. Since the maximum allowable pressure for PTFE is much lower, the load was 2 kg. Velocity was 0.5 m/s. The value of sliding distance was selected so as to achieve about a 5 mm scar length. The specimen was only 10 mm in width; hence, too deep penetration of the ring may have resulted in impact with the vice jaws. Therefore, the sliding distance was 100 m for PTFE, 1000 m for PE-HD, and 2000 m for PA6. The block scar volume was based on the width of the scar, and the calculation was performed by using the formula shown in the international standard concerning block-on-ring wear test **[L. 10]**.

As for wear, the measurement procedure was similar to the coefficient of friction measurements. During the first stage of measurements, the specimen was placed between vice jaws, and tests were carried out with the non-deformed specimen. During the second stage, the specimen was deformed, and the precise value of strain was obtained using a microscope. Measurements of the deformed specimen were carried out beside the place of the measurement of the non-deformed specimen. Due to this procedure, each specimen was examined in a deformed and a non-deformed state, and it was mounted only one time. Without reassembling the specimen after one test, better reliability of measurements was assured. Gathered data allowed conducting a comparison of non-deformed and deformed states. The results are presented as a comparison of volume loss for ε = 0% and ε ≠ 0%.

RESULTS

Microhardness

– During microhardness measurements, 3 samples were tested in terms of each material. Values obtained for particular specimens differed only slightly. The most important fact is that trend lines drawn for particular specimens were very similar. Therefore, **Figure 3** shows values measured for one specimen selected for each material.

The analysis of hardness measurements revealed that investigated plastics act differently during compression. The most significant change was observed in terms of PTFE.

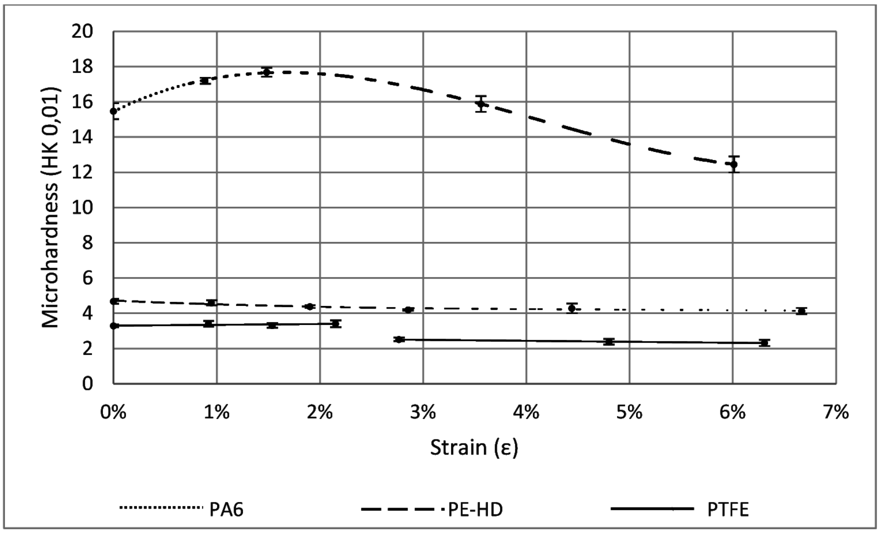

Fig. 3. Microhardness of non-deformed and deformed PE-HD, PTFE and PA6 the trend lines and confidence intervals (1-α = 0.95)

Rys. 3. Mikrotwardość nieodkształconych i odkształconych PE-HD, PTFE i PA6 oraz przedziały ufności jej wartości (1-α = 0,95) i linie trendu

As for microhardness, PE-HD appears to be the least sensitive to deformation. When the specimen was deformed to ε ≈ 2.5%, microhardness decreased only by 10%. In terms of PE-HD, microhardness decreased with deformation under compression. When strain is larger than 2.5% (there is mainly plastic deformation in the polymer) the value of microhardness hovers.

The increase in microhardness is observed only in terms of PA6. When this plastic is compressed to ε ≈ 1.5%, microhardness increased by about 10%. When strain is 1.5%, there is a maximum value of microhardness. When strain is getting larger than 1.5%, the value of microhardness decreases. Therefore, when the strain is about 6%, the value of microhardness is about 20% lower than for non-deformed polymer.

The coefficient of friction

The main aim of the research is to compare properties of deformed and non-deformed plastics. Therefore, the results of the coefficient of friction and wear are presented as a percentile decrease/increase of values measured for non-deformed specimen.

The research shows that the influence of deformation on the coefficient of friction is insignificant **(Tab. 1)**. The changes are up to 3%. Exceptionally, when PA6 was deformed to ε ≈ 6%, the coefficient of friction decreased by about 6%.

Wear

When strain is up to about 2.5% (there is mainly elastic deformation in the polymer) changes in wear are insignificant **(Tab. 2)**. During tests of specimens made of particular polymers, a decrease and an increase are observed.

Table 1. Changes in the friction coefficient (in comparison to non-deformed polymer) and confidence intervals (1-α = 0.95) for the pair deformed polymer – steel (A1). Sliding velocity v = 10 mm/s, contact pressure p = 3 MPa

Tabela 1. Zmiany współczynnika tarcia (w porównaniu z nieodkształconym polimerem) oraz przedziały ufności ich wartości (1-α = 0,95) dla pary odkształcony polimer – stal (A1). Prędkość ślizgania v = 10 mm/s, nacisk p = 3 MPa

Polymer \ Strain	~1.5%	~6%
PTFE	**+1.9% ↑** ± 0.8%	**+3.4% ↑** ± 0.7%
PE-HD	**-3.0% ↓** ± 0.7%	**+1.3% ↑** ± 4.1%
PA6	**+2.4% ↑** ± 1.0%	**-6.1% ↓** ± 0.8%

Significant changes were observed when plastic deformation occurred in plastics. In terms of PTFE, when strain was about 6%, there was a 20% increase in wear volume loss in comparison with the non-deformed specimen. As for PE-HD, an increase was about 40%. Exceptionally, in terms of PA6, wear did not increase when the specimen was deformed.

Table 2. Changes in wear volume loss (in comparison to non-deformed polymer) and confidence intervals (1-α = 0.95) for the pair deformed polymer – steel (A1). Wear test parameters described in the text

Tabela 2. Zmiany zużycia objętościowego (w porównaniu z nieodkształconym polimerem) oraz przedziały ufności ich wartości (1-α = 0,95) dla pary odkształcony polimer – stal (A1). Parametry współpracy w skojarzeniu podane w tekście

Polymer \ Strain	~1.5%	~6%
PTFE	**+2.0% ↑** ± 6.8%	**+19.5% ↑** ± 8.5%
PE-HD	**-1.4% ↓** ± 6.5%	**+40.6% ↑** ± 7.0%
PA6	**-1.8% ↓** ± 6.6%	**+2.1% ↑** ± 6.5%

DISCUSSION

Tension and compression are different processes. Therefore, it may appear that they cause entirely different effects as far as the coefficient of friction, microhardness, and wear are concerned. However, the research conducted by the author of this publication proved that the previously mentioned statement is inaccurate. It is possible to acknowledge a lot of similarities between the influence of tension and the influence of compression on plastics' properties.

During the deformation under tension as well as deformation under compression, a decrease in microhardness was observed. However, the scale and the course of changes depend on the material. For instance, in terms of PA6, during deformation under tension, an initial increase in microhardness was not observed (as opposed to deformation under compression). Moreover, the sudden change of PTFE microhardness was not observed during deformation under tension (as opposed to deformation under compression). As for PE-HD, changes in microhardness are similar during tension and compression.

During deformation under tension, the change of the coefficient of friction was observed when strain is large (a few dozen percent). When strain is lower, a change is not reported (in terms of tension and compression). Subsequently, the deformation under tension caused increased wear. A significant change was observed when strain was larger than 5%. The most significant increase was reported in terms of PTFE. PE-HD was slightly less sensitive to deformation under compression. As far as PA6 is concerned, only a minor impact on wear was noticed.

The comparison of results of tension and compression reveals that changes in hardness and wear are effects of deformation. It does not matter if it is tension or compression. In general, when strain is larger than 5% (there is mainly plastic deformation in the polymer), there is an increase in wear and a decrease in microhardness. However, it is necessary to clarify if it is tension or compression to assess the scale of change.

Materials used during the research are polymers with no additives. However, composites that are based on polymers are used in machines and devices. Additives reduce wear. For instance, an addition of bronze powder may reduce wear a few dozen times. Consequently, in terms of composites, the influence of deformation on wear may be different than for polymers with no additives. Therefore, additional research ought to be conducted.

CONCLUSIONS

- In terms of examined plastics' deformation under compression and maintaining this deformation causes a significant change in microhardness and wear. The coefficient of friction does not change significantly.
- As for all examined plastics (PTFE, PE-HD, and PA6) the value of microhardness is lower than for the non-deformed specimen when strain is about 6% (there is mainly plastic deformation in the polymer). The reduction in microhardness is up to 30% (PTFE). In terms of PE-HD, the reduction in microhardness is 10%, and in terms of PA6, the reduction is 20%.
- It is impossible to formulate a general statement about a trend in changes in microhardness. It is different for each plastic. In terms of PTFE, a sudden change in microhardness was observed (strain was about 2.5%). Before and after reaching $\varepsilon \approx 2.5\%$, the value of microhardness hovers. When PE-HD is compressed up to strain 2.5% (there is mainly elastic deformation in the polymer) and a reduction in hardness is observed. After reaching $\varepsilon \approx 2.5\%$, the value of microhardness hovers. As for PA6, when strain is up to 1.5%, an increase in microhardness is observed (by about 10–15%). After reaching $\varepsilon \approx 1.5\%$, a decrease in microhardness was observed, and when strain is 6%, microhardness is reduced by 20% in comparison with a non-deformed specimen.
- The most significant changes in wear were observed in terms of PTFE and PE-HD when strain was about 6%. In comparison with a non-deformed specimen, there was an increase in wear volume loss of about 20% (PE-HD) and 40% (PTFE). When strain was up to 2.5% (there was mainly elastic deformation in the polymer) no significant change of wear was reported. As far as PA6 is concerned, no significant change of wear was observed even when strain was about 6%.
- In terms of PTFE, PA6 and PE-HD deformation under tension causes change in microhardness even when there was mainly elastic deformation in the polymer. It is worth being aware of this phenomenon, since the elastic deformation region is regarded as completely safe and permissible.
- In terms of PE-HD and PTFE, even small strain (up to $\varepsilon \approx 6\%$ – there is mainly plastic deformation in the polymer) causes a significant increase in wear. Therefore, plastic sliding elements ought to work when strain is limited. General advice about assembly ought to be formulated and introduces during the fastening of plastic sliding elements.

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