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Analysis of Tribotechnical Properties and Comparative Evaluation of Polymeric Materials and Rubbers Used in Rolling Stock



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ABSTRACT

Rubber materials are widely used in friction assemblies of railway rolling stock. Rubbers are used oil seals, other various seals, shock absorbers, corrugated hoses, sleeves, sealing rings, etc. During operation, rubbers are exposed to various mechanical influences that cause wear, cracks, abrasion, dents, burn-throughs, etc., which can lead to the failure of the entire unit and unforeseen unscheduled repairs of the rolling stock. Any failure on the route together with unplanned repairs incur heavy economic losses.

Currently, the issue of wear of rubbers in rubber-steel tribo-pairs has not been sufficiently studied in case of supply of lubricant to the friction zone and of wear caused by a free and fixed abrasive. There is ongoing research on the possibility of replacing rubber products with other polymeric materials, which have shown significantly better results in tribological tests, both in terms of friction coefficients and in the wear mechanism. The data obtained will

make it possible to choose the most optimal options for materials that can act as a replacement for standard rubber products in rolling stock friction assemblies.

The paper presents the results of tribological tests of thermoplastic polyurethanes (TPU), ultra-high-molecular-weight polyethylene (UHMWPE) and polypropylene (PP2015) in comparison with rubber based on nitrile butadiene rubber (NBR). The tests were carried out according to two schemes: «plane (tested sample) – bushing» and «plane (tested sample) – generatrix of a rubber disk with supply of abrasive grain to the friction zone».

The objective of the work is to determine the dependence of the change in friction coefficients on load and sliding speed, as well as the dependence of seizure pressures of tribo-pairs on speed, weight loss of samples after wear tests with a free and fixed abrasive, the morphology of wear surfaces, and wear mechanisms of polymer materials and rubbers.

Keywords: transport, railway, rolling stock, friction coefficient, polymers, damping material, tribotechnical properties, sliding speed, abrasive wear.

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Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

Application and improvement of damping polymer elements are directly associated with improvement of dynamic characteristics of wagons and locomotives during their interaction with the upper structure of the railway track (e.g., [1]). One of the main challenges is the need to improve the dynamic properties of elastic damping elements.

Possibility to use damping polymer materials in friction assemblies of rolling stock is being considered to increase economic efficiency. The technical requirements for modern design of railway shock absorbers are defined by their operating conditions, which imply reliable operation under static, cyclic and shock loads, at low and high temperatures, in contact with the environment, which largely depends on the type of damping material. It should be noted that, despite the extensive experience in studying physical and mechanical properties of polymers and composite polymer materials, the issue of wear of polymers in polymer-steel tribo-pairs has not been sufficiently studied in case of presence of lubricants and of wear caused by a free and fixed abrasive. Therefore, additional studies are required for their comparative evaluation. A study [2] of a composite polytetrafluoroethylene (PTFE) bearing was carried out by modelling wear with a steel shaft. The effect [3] of thermal aging of oil on frictional and wear-resistant properties of NBR has been studied. It has been determined how the surface roughness [4] affects friction and wear resistance of NBR. The study [5] has performed modelling and experimental study of translational hydraulic seal wear. Upon swelling NBR with the standard solvent IRM 903 [6], wear was 1,1 times higher than in the non-swollen sample. The wear resistance [7] of friction units of borehole pumps with seals made of directionally reinforced polymer composites has been determined. Graphite polytetrafluoroethylene (PTFE) and polyamide (PI) composites were tested with tool steel with lubrication and the addition of finely dispersed quartz sand [8].

An experimental study [9] of performance characteristics of a high-speed polymer thrust bearing with oil lubrication has been carried out. The influence of pressure and sliding speed on the coefficient of friction of polyurethane elastomers of different hardness during friction against steel using a grease has been determined

in [10]. The tribological characteristics of ultra-high-molecular-weight polyethylene (UHMWPE) were obtained [11] with respect to TiAl_6V_4 and $\text{CoCr}_{28}\text{Mo}$ alloys.

The objectives of the work were: to determine the dependence of the change in friction coefficients on load and sliding speed for thermoplastic polyurethanes (TPU), ultra-high-molecular-weight polyethylene (UHMWPE) and polypropylene (PP2015) in comparison with rubber based on nitrile butadiene rubber (NBR), as well as the dependence of seizure load of tribo-pairs on speed; to determine the weight loss of specimens after wear tests with a fixed and unfixed abrasive, as well as to study the morphology of wear surfaces, and the mechanisms of wear of polymer materials and rubbers.

MATERIALS AND METHODS OF RESEARCH

Samples of TPU 50D2S10, 60D2S10, UHMWPE, PP2015, NBR were selected for friction and wear testing. The samples were a plate with dimensions of $20 \times 70 \times 2$ mm, which was glued to plywood with dimensions of $20 \times 70 \times 12$ mm. Tribological tests were carried out according to the scheme «plane (tested sample) – bushing (steel mandrel with silicon carbide-based abrasive paper with a grain size of $120 \mu\text{m}$ glued to its end, or a 40X steel bushing with hardness HRC 49–54). The end of the bushing was processed with sandpaper of various grain sizes (P180, P220, P600, P2400). The sliding speed and pressure on the sample varied discretely in the range of 0,1–3,5 m/s and 2–10 MPa, respectively. Hydraulic oil MGE10A was used as a lubricant when testing polymer samples against steel, with one drop per second supplied to the friction zone. Free abrasive wear tests were carried out by rubbing a flat sample against the generatrix of the rubber disk surface. Quartz sand with particle sizes from 0,2 to 0,6 mm was fed into the friction zone. The tests were carried out at normal atmospheric pressure and room temperature. The test load was 15 N, the test duration was 5 minutes per single sample. After each test, the samples were cleaned from abrasive particles using a cylinder with dry compressed air. Three samples of each material were tested. The weight loss of the samples was determined using an analytical balance VIBRA HT-220CE. The wear amount was determined as the arithmetic average of values obtained from three samples.



Technical characteristics of TPU ^{1, 2, 3}

Material grade	Hardness, Shore	Density, g/cm ³	Tensile strength, MPa	Elongation at break, %
TPU 50D2S10	52 D	1,18	45,0	450
TPU 60D2S10	60 D	1,18	55,0	320
UHMWPE	64 D	0,93	25	50
PP 02015	70 D	0,9	29	400
NBR	75 A	1,3	25	425

¹ Official website of «RT-EPOFLEX». Section «Scope of application». Automobile. [Electronic resource]: <http://rtplp.ru/sfera-primeneniya/>. Last accessed 13.04.2021.

² Official website of «Polymer company. Plastprominvest». Section «Products». Balen 02015. [Electronic resource]: <http://ppinvest.ru/produkcija/blok-sopolimeri-propilena-etilena/balen-02015.html>. Last accessed 13.04.2021.

³ Official website of Trading and manufacturing company «RUBICOM». Section «Information». Nitrile butadiene rubber (NBR) [Electronic resource]: <https://www.rubicom.ru/info/articles/kauchuki/butadien-nitrilnyy-kauchuk-bnks/>. Last accessed 13.04.2021.

RESULTS OF EXPERIMENTAL STUDIES

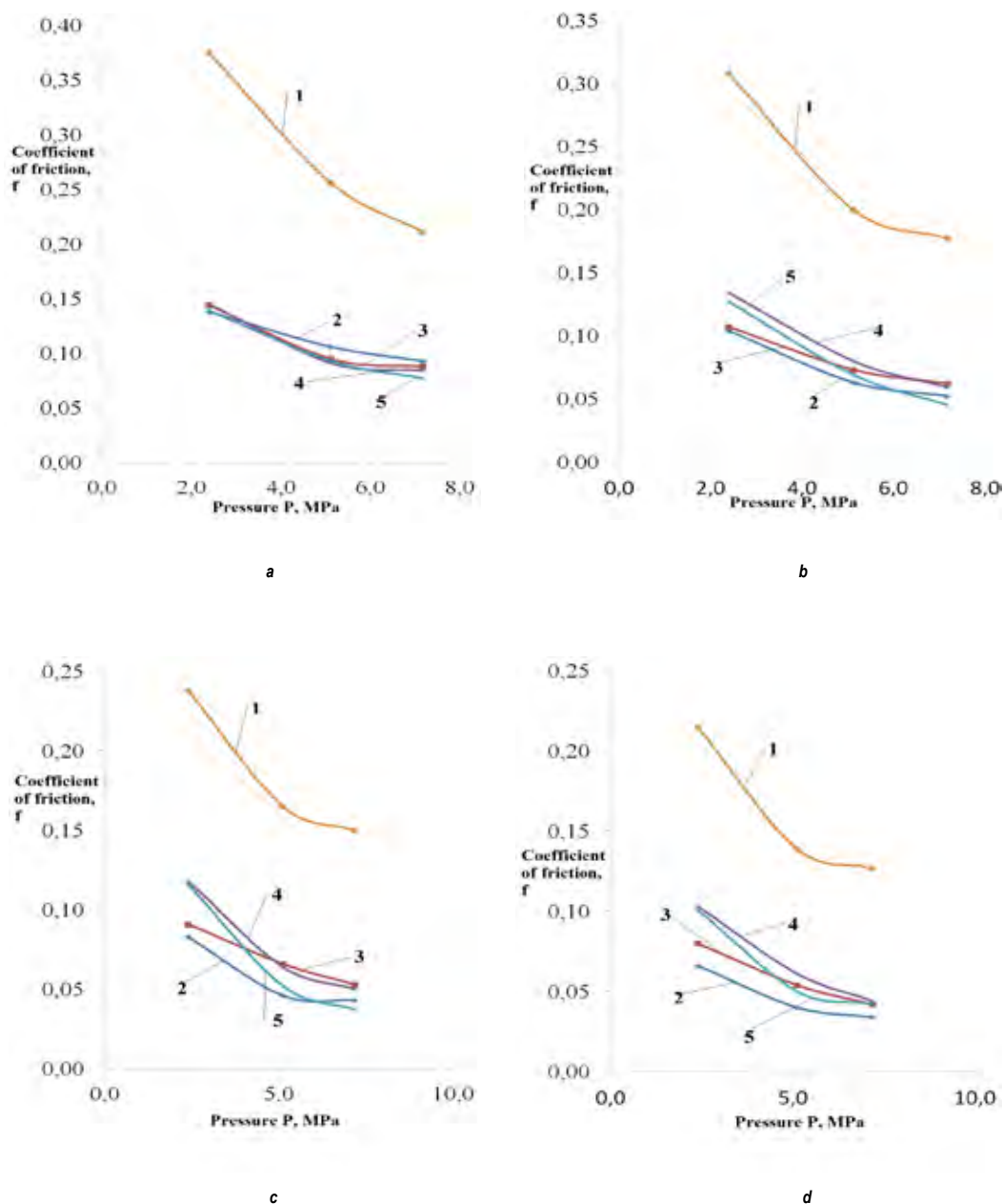
Pic. 1 (a – P180, b – P220, c – P600, d – P2400) presents the results which reflect the dependence of the friction coefficient on the pressure and roughness of the surface of the annular sample, depending on processing with sandpaper and the size of abrasive grain. The friction coefficient of NBR sharply decreased from 0,3–0,35 to 0,2 at a pressure of 2 MPa (Pic. 1a, b) and from 0,2–0,25 to 0,13–0,15 (Pic. 1c, d). For PP2015, the friction coefficient also decreased with an increase in pressure and a decrease in roughness of the steel surface with maximum values of 0,08–0,14, and the minimum values of 0,04–0,1. The friction coefficient of UHMWPE was higher in comparison with other materials with the maximum values of 0,09–0,15 and the minimum values of 0,05–0,11. TPU 50D2S10 polyurethanes had lower friction coefficients compared to TPU 60D2S10 polyurethanes, except for tests with steel samples treated with P180 sandpaper. The minimum values of friction coefficients of polyurethanes were 0,04–0,06 for 50D2S10 and 0,05–0,08 for 60D2S10.

In general, the coefficients of friction, depending on pressure, tended to decrease in their value. A decrease in roughness of the steel surface led to a decrease in friction coefficients of friction for all materials with an increase in pressure in the tribo-pair.

Pic. 2 (a – P180, b – P2400) shows the regularities of the change in friction coefficients on sliding speed and roughness of the steel sample. For all materials, with an increase in sliding speed from 0,2 to 0,6 m/s, a decrease in friction coefficients was observed. So, for NBR, friction coefficients decreased from maximum values of 0,37 and 0,22 to 0,35 and 0,2,

depending on roughness of the steel surface (Pic. 2a, b), respectively. For the rest of polymers, initial values of friction coefficients, when processing steel with P180 sandpaper, were practically the same and amounted to 0,14–0,15. With an increase in sliding speed from 0,6 to 1,3 m/s, friction coefficients of all materials increased and were higher than at a speed of 0,2 m/s. The friction coefficient of PP2015 had maximum values of 0,14–0,16 (Pic. 2a) and minimum values of 0,09–0,11 (Pic. 2b). The friction coefficient of UHMWPE had lower friction coefficients of 0,12–0,125 at sliding speeds of 0,8–1,3 m/s (Pic. 2a) and higher friction coefficients of 0,09–0,11 compared to other polymers at the same speeds. This may be due to the higher molecular component of the coefficient of friction when processing steel with P2400 sandpaper, providing minimum roughness of the friction surface. TPU 50D2S10 polyurethanes with coarser steel surface had friction coefficients higher than 60D2S10 polyurethanes (Pic. 2a). With a smoother steel surface, TPU 50D2S10 friction coefficients had the minimum values of 0,06–0,08, while TPU 60D2S10 showed values of 0,07–0,11. For all materials, there was an increase in friction coefficients with an increase in speed above 0,6 m/s.

Pic. 3 (a – P180, b – P2400) shows the dependence of the change in the seizure load on sliding speed. For all the materials under study, with an increase in the sliding speed, the seizure load decreased. So, for NRB samples, with a coarser roughness of the steel friction surface, at a pressure of 7 MPa, jamming occurred at a sliding speed of 0,2 m/s, and with a smoother steel surface, it occurred at a speed of 0,4 m/s. TPU 50D2S10 polyurethanes had higher seizure



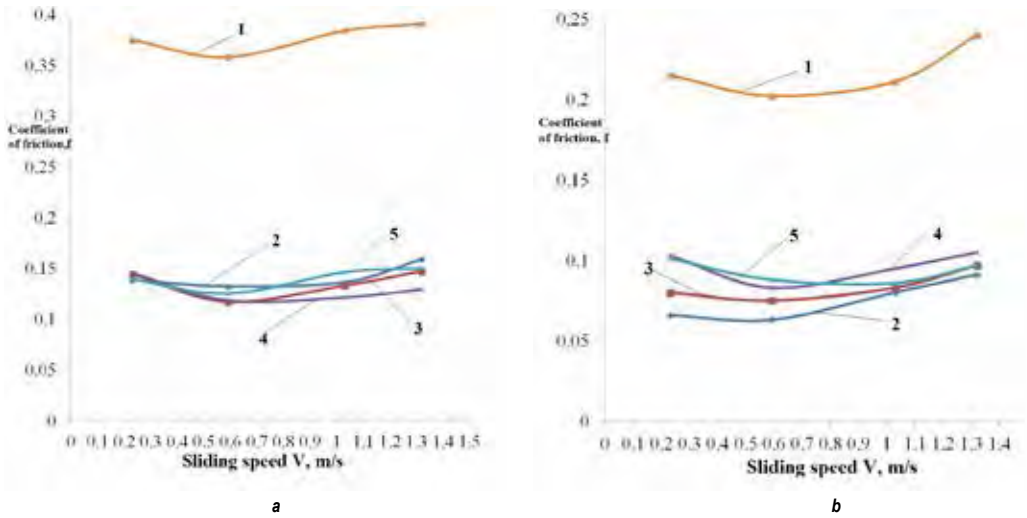
Pic. 1. Dependences of friction coefficients on pressure for steel 40X with sandpaper processing: a – P180, b – P220, c – P600, d – P2400. 1 – NBR, 2 – 50D2S10, 3 – 60D2S10, 4 – UHMWPE, 5 – PP2015 (compiled by the authors).

loads than TPU 60D2S10 samples over the entire speed range. UHMWPE samples had intermediate jamming loads between TPU and PP2015. The highest seizure loads were obtained for PP2015 samples, regardless of surface roughness of the steel bushing end.

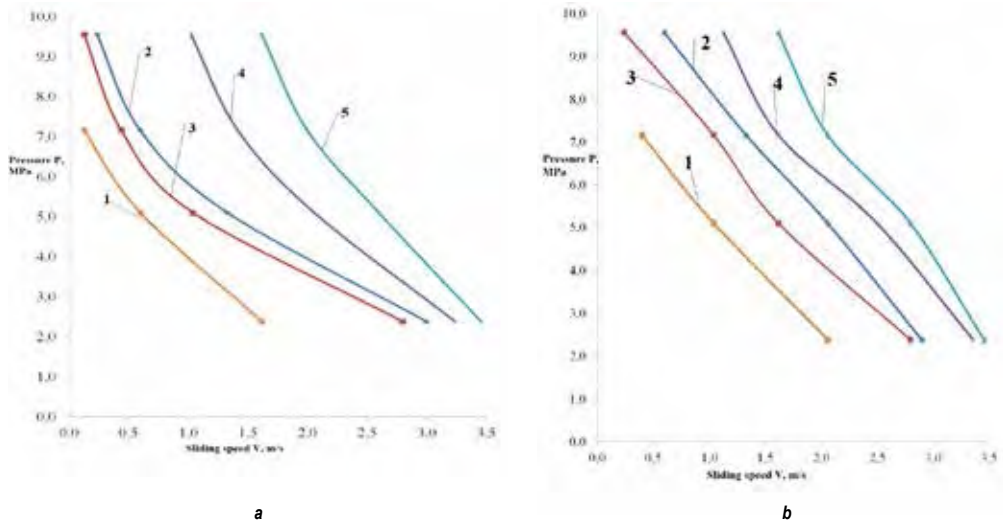
Pic. 4a, b shows the results in the form of dependences of the friction coefficient on normal pressure and sliding speed when tested on a fixed abrasive.

With increasing pressure, coefficients of friction decrease for all types of polymers and NBR. The obtained values of friction coefficients can be arranged as they increase in the following order: 0,3–0,36 for PP2015, 0,33–0,44 for UHMWPE, 0,38–0,55 for 50D2S10, 0,4–0,58 for 60D2S10 and 0,85–0,98 for NBR. An increase in sliding speed from 0,12 to 0,23 m/s led to an insignificant increase in coefficients of friction for the studied polymers. So, for PP2015

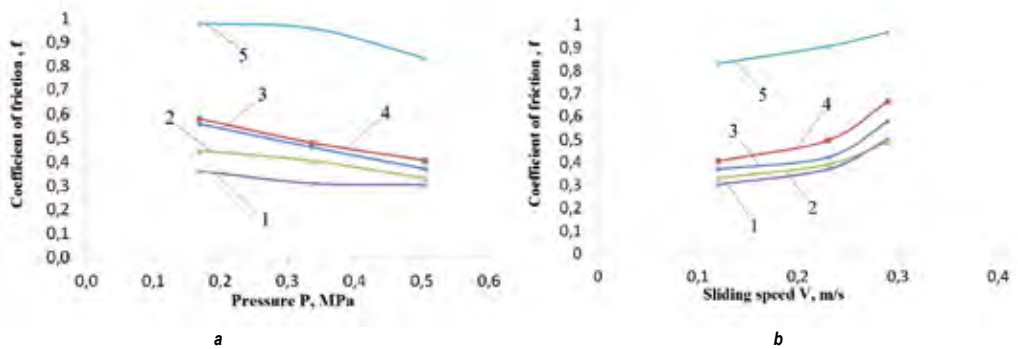




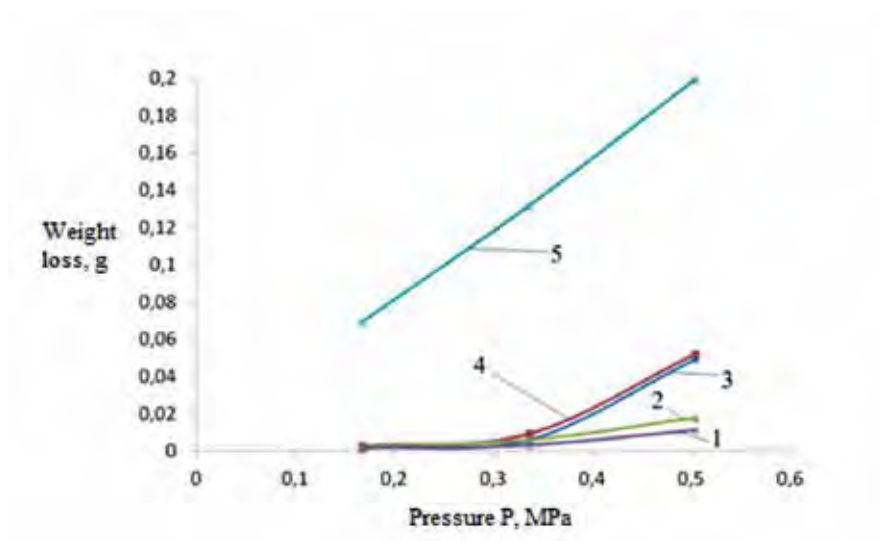
Pic. 2. Dependencies of friction coefficients on sliding speed for steel 40X with sandpaper processing:
a – P180, b – P2400. 1 – NBR, 2 – 50D2S10, 3 – 60D2S10, 4 – UHMWPE, 5 – PP2015 (compiled by the authors).



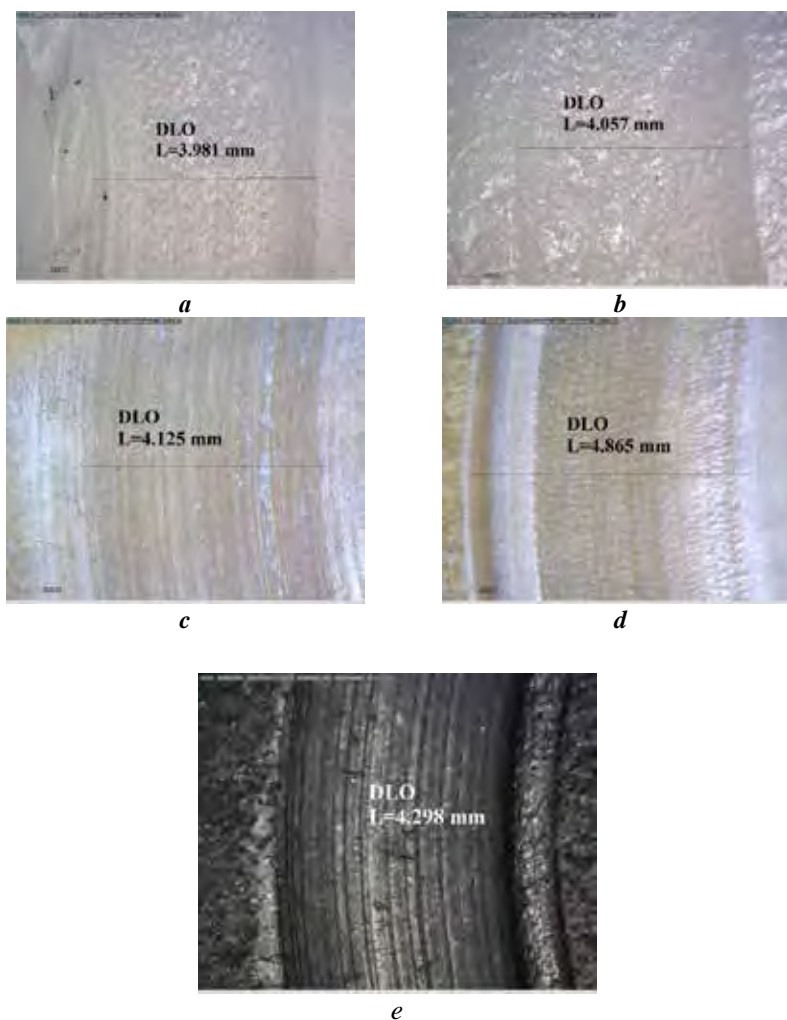
Pic. 3. Dependencies of the seizure load on sliding speed for steel 40X with sandpaper processing:
a – P180, b – P2400. 1 – NBR, 2 – 50D2S10, 3 – 60D2S10, 4 – UHMWPE, 5 – PP2015 (compiled by the authors).



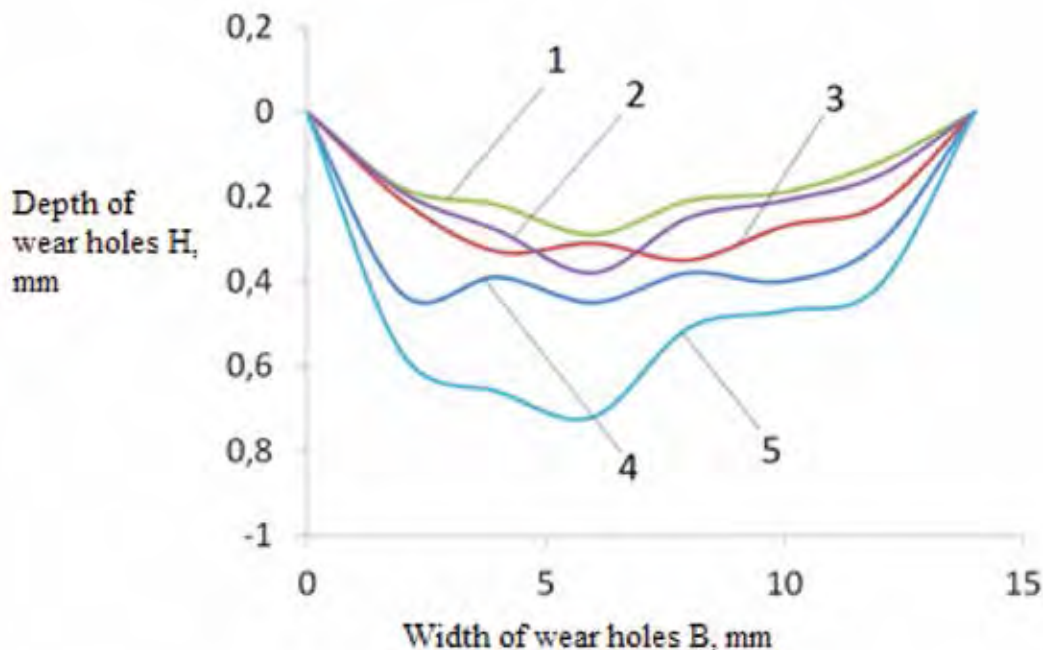
Pic. 4. Dependence of coefficients of friction of polymers on pressure (a) and sliding speed (b), case of fixed abrasive:
1 – PP2015, 2 – UHMWPE, 3 – 50D2S10, 4 – 60D2S10, 5 – NBR (compiled by the authors).



Pic. 5. Dependence of the weight loss of polymers on the test pressure, case of fixed abrasive:
 1 – PP2015, 2 – UHMWPE, 3 – 50D2S10, 4 – 60D2S10, 5 – NBR (compiled by the authors).



Pic. 6. Morphology of friction surfaces of polymers and NBR rubber during testing, case of fixed abrasive:
 a – PP2015, b – UHMWPE, c – 50DS210, d – 60DS2010, e – NBR (compiled by the authors).



Pic. 7. Profiles of wear holes of materials: 1 – 50DS210, 2 – 60DS210, 3 – UHMWPE, 4 – PP2015, 5 – BNK (performed by the authors).

and UHMWPE, it increased from 0,32 to 0,36. With a further increase in speed to 0,3 m/s, the friction coefficient was 0,5 and 0,49 for PP2015 and UHMWPE, respectively. The coefficient of friction of NBR 0,8–0,9 increased proportionally in the entire range of sliding speeds.

Pic. 5. shows the weight loss of samples due to the change in the pressure in the contact area during testing.

For NBR rubbers, the weight loss increased in proportion to the pressure. The wear of TPU samples at low pressures up to 0,34 MPa is insignificant, with a further increase in pressure to 0,54 MPa for both 50D2S10 and 60D2S10 it increases from 0,01 to 0,04 g. The minimum weight loss was obtained for PP2015 polypropylene. Pic. 6 shows the morphology of friction surfaces of samples.

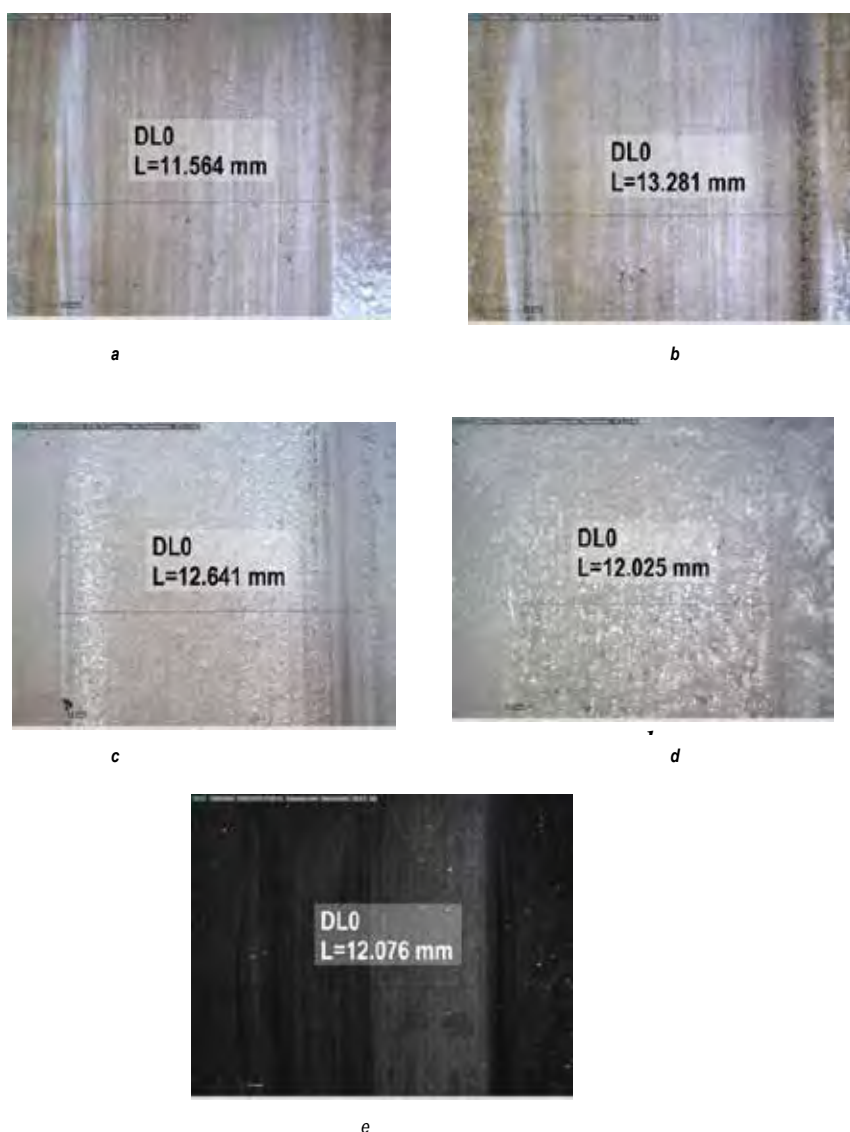
The friction surfaces of PP02015 polypropylene and UHMWPE with a minimum wear value of 0,003 and 0,004 g, respectively, did not have deep grooves or grooves in the direction of sliding of the fixed abrasive grain. The waviness of the surface indicates the gradual accumulation of damage and separation of wear particles by the fatigue mechanism. The friction surfaces of samples 50DS210 and NBR had

marks in the sliding direction along the entire length. It can be assumed that micro-cutting was the prevailing wear mode. For 60DS2010 samples, the wave height was minimal, and the wear pattern can be attributed to the fatigue wear mechanism during friction against the fixed abrasive grain.

Pic. 7 shows the profiles of the wear holes of polymeric materials and NBR when tested with an unfixed abrasive.

In contrast to tests with a fixed abrasive, the minimum weight loss was shown by TPU50DS210 and 60DS2010 samples. Samples of UHMWPE moved to the third place. The largest weight loss was shown by PP2015 and NBR samples, respectively. Pic. 8 shows fragments of wear holes of material during friction against a free abrasive.

The friction surfaces of 50DS210, 60DS2010 and NBR had longitudinal notches in the direction of sliding of the abrasive grain and the wear mechanism can be attributed to micro-cutting. The waviness of the surface of UHMWPE and PP2015 samples indicates gradual accumulation of damage and separation of wear particles by the fatigue mechanism. Various test results for friction with free and fixed abrasive



Pic. 8. Morphology of friction surfaces of polymers and rubber NBR during testing, case of free abrasive:
a – 50DS210, b – 60DS2010, c – UHMWPE, d – PP2015, e – NBR (performed by the authors).

grain indicate that when testing TPU PP2015, sandpaper was coated with polymer particles due to adhesion and the wear rate and coefficient of friction decreased. For polymers 50DS210, 60DS2010, the minimum loss of mass during friction in case of a free abrasive indicated that their hardness was higher than that of a rubber disc, and some of abrasive particles were simply pressed into the generatrix of the disc. Despite different results, both test methods complemented each other and gave a complete characteristic of polymeric materials used in the assemblies of

machines and mechanisms, when it is possible to act on the friction surface with a fixed or a free abrasive grain.

DISCUSSION OF RESULTS

The analysis of the studies carried out by international authors shows a tendency to expand the use of polymeric materials in polymer-steel tribo-pairs in the presence of liquid and plastic lubricants. NBR samples are inferior in all respects to TPU polyurethanes, UHMWPE and PP2015 samples. Currently, in a significant



number of rolling stock friction assemblies, the now operated rubber seals, shock absorbers, gaskets, corrugated hoses are used, which can be successfully replaced with more reliable materials with lower friction coefficients and higher seizure loads compared to NBR. The use of TPU, UHMWPE and PP2015 will increase reliability and service life of rolling stock friction assemblies. Materials such as TPU 50DS210, 60DS2010 and UHMWPE can be further used in friction assemblies as a replacement for rubber products for manufacture of sealing rings, oil seals, gaskets, and corrugated hoses and tubing. PP2015 polypropylene can be used instead of rubber in control panels, tipping mechanisms and devices inside the rolling stock.

CONCLUSION

Obtained regularities of the change in coefficients of friction of 50D2S10, 60D2S10 polyurethanes, UHMWPE and PP2015 on pressure and sliding speed showed that these materials are superior to NBR regardless of the grade of surface roughness of 40X steel. The seizure load of the proposed polymeric materials is higher than that of NBR in the entire range of studied loads and speeds.

Regularities of changes in the coefficients of friction and weight loss of samples on pressure have been also identified following the results of tests with fixed and free abrasive. The coefficient of friction of PP2015 polypropylene had values of 0,3–0,36, while for NBR it was 2,5 times higher and amounted to 0,85–1,0 with friction against a fixed abrasive. UHMWPE samples showed a stable result in relative weight loss when tested with a free and fixed abrasive. The smallest wear was observed for PP2015 and 50DS210, 60DS2010 samples with friction against a fixed abrasive and a free abrasive, respectively.

REFERENCES

1. Kurzina, E. G. Improvement of damping elastic polymer elements of freight wagon running gears. Ph.D. (Eng) thesis [Sovershenstvovanie dempfiruyushchikh uprugikh polimernykh elementov khodovykh chastei

gruzovogo vagona. Dis...kand. tekhn. nauk]. Moscow, MIIT publ., 2019, 228 p.

2. Tao, Guan; Peng Hui; Yong, Gao; Kun, Yang. Condition monitoring of PTFE composite material bearing through the correlation between lubricant condition and wear simulation. Fourth International Conference on Transportation Information and Safety (ICTIS), 2017, pp. 1028–1033. DOI: 10.1109/ICTIS.2017.8047896.

3. Bingqi, Jiang; Xiaohong, Jia; Zhugang, Wang; Tao, Wange; Fei, Guo; Yuming, Wang. Influence of Thermal Aging in Oil on the Friction and Wear Properties of Nitrile Butadiene Rubber. *Tribology Letters*, 2019, pp. 67–86. DOI: <https://doi.org/10.1007/s11249-019-1201-8>.

4. Dong, Feng; Ming-xue, Shen; Xu-dong, Peng; Xiang-kai, Meng. Surface Roughness Effect on the Friction and Wear Behaviour of Acrylonitrile–Butadiene Rubber (NBR) Under Oil Lubrication. *Tribology Letters*, 2017, pp. 65–10. DOI: <https://doi.org/10.1007/s11249-016-0793-5>.

5. Angerhausen, J., Woyciniuk, M., Murrenhoff, H. [et al]. Simulation and experimental validation of translational hydraulic seal wear. *Tribology international*, 2019, Vol. 134, pp. 296–307. DOI: <https://doi.org/10.1016/j.triboint.2019.01.048>.

6. Balasooriya, W., Schritteser, B., Chao, Wang; Hausberger, A., Pinter, G., Schwarz, T. Tribological Behavior of HNBR in Oil and Gas Field Applications. *Lubricants*, 2018, pp. 6–10. DOI: <https://doi.org/10.3390/lubricants6010020>.

7. Krasnyi, V. A., Maksarov, V. V. Improving wear resistance of friction assemblies of oil-well pumps having seals from directionally reinforced polymer composites. *Chemical and Petroleum Engineering*, 2017, Vol. 53, pp. 121–125. DOI: <https://doi.org/10.1007/s10556-017-0306-x>.

8. Gheisari, R., Polycarpou, A. A. Tribological performance of graphite-filled polyimide and PTFE composites in oil-lubricated three-body abrasive conditions. *Wear*, 2019, pp. 436–437, 203044. DOI: <https://doi.org/10.1016/j.wear.2019.203044>.

9. Jie, Zhou; Blair, B., Argires, J. [et al]. Experimental Performance Study of a High Speed Oil Lubricated Polymer Thrust Bearing. *Lubricants*, 2015, Vol. 3, pp. 3–13. DOI: <https://doi.org/10.3390/lubricants3010003>.

10. Capanidis, D., Sokolska, J. Effect of pressure and sliding speed on the friction coefficient of polyurethane elastomers (EPUR) of different hardness during their friction on steel when lubricating with grease. *Tribologia*, 2019, Vol. 5, pp. 33–41. DOI: 10.5604/01.3001.0013.6559.

11. Guezmil, M., Bensalah, W., Mezlini, S. Tribological behavior of UHMWPE against TiAl₃V₄ and CoCr₂₈Mo alloys under dry and lubricated conditions. *Journal of the Mechanical Behavior of Biomedical Materials*, 2016, Vol. 63, pp. 375–385. DOI: <https://doi.org/10.1016/j.jmbm.2016.07.002>.

12. Prints, A. N., Biryukov, V. P. Investigation on tribological characteristics of polymer materials during abrasive wear [Issledovanie tribologicheskikh kharakteristik polimernykh materialov pri abrazivnom iznashivani]. XXXII International Innovative Conference of Young Scientists and Students on Mechanical Engineering Problems: Proceedings of the conference. Moscow, 2021, pp. 228–234. ●

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