Analysis of micromechanical and tribotechnical properties of fluoropolymers during friction on 40Kh steel

Vladimir Biryukov[1*] and *Anton* Yakubovsky[1]

[1]Mechanical Engineering Research Institute of the Russian Academy of Sciences, 4 Maly Kharitonyevsky Pereulok, 101990 Moscow, Russia

Abstract. The paper presents the results of micromechanical and tribotechnical tests of samples of polytetrafluoroethylene, radiation-modified (PTFE – RM according to modes A and B), coked in comparison with the PTFE standard (Fluoroplast -F4). The influence of the surface roughness of a 40Kh steel counter-tile on the coefficients of friction against time at a constant sliding speed is considered. Micromechanical tests were carried out using the method of instrumental indentation with a triangular Berkovich diamond pyramid. Tribotechnical tests were performed on a friction machine with a vertical axis of rotation of the spindle according to the scheme "the end of the sample of the fluoropolymer disk is the end of the counter-flange of the annular sleeve (steel 40Kh)" without lubrication and when the friction pair is lubricated with MGE-10A hydraulic oil. It was found that during friction without lubrication, PTFE samples had the maximum friction coefficients, and F4K20 samples had the minimum friction coefficients when working with 40X steel counter-tiles treated with P180 sandpaper. PTFE-RM (A) samples had the best wear resistance, followed by decreasing F4K20, PTFE – RM (B) and PTFE under friction without lubrication. In the presence of lubricant, the samples of the PTFE standard were inferior in wear resistance to the F4K20 samples, but were 5-7% better than the samples of PTFE-RM (B) and (A), respectively.

1 Introduction

Due to their low cost, low density, high ductility, good tribotechnical properties, as well as ease of processing, polymers are increasingly used to replace metal parts in mechanical systems. Polymers can be used in many technological applications such as brakes, gears and electrical appliances [1]. Under high mechanical loads or contact pressures, the use of polymers may be difficult. To eliminate this disadvantage, the introduction of various fillers is used to strengthen them. Fillers of various shapes and sizes (fibers, microparticles, nanoparticles, etc.) are used. Interest in the development of polymer composites is growing faster than in metals, due to their use in a wide range of mechanical parts [2,3]. Reinforcement of the polymer matrix with fibers or fillers can change the tribological,

* Corresponding author: laser-52@yandex.ru

mechanical and thermal properties of the polymer [4-7]. In [8], the main attention is focused on the analysis of compositions by combining polyesteresterketone (PEEK) and carbon nanotubes (MWCNTs) to use their synergistic effect, increase mechanical strength and tribological properties.

Radiation modification of polymers is an ever-expanding field of work that is attracting increasing interest from the industry.

The use of this method requires a complete understanding of the effects of radiation on polymer materials, especially when the goal is to improve their properties to higher levels [9-10]. The study of the effect of radiation [11] on samples of a mixture of polypropylene (PP) and polyethylene (PE) with different weight ratios at radiation doses of 10, 30, 50, 70 and 100 kGy was performed at a Co 60 source. It was found that the melting temperatures of the mixtures were close to the melting temperatures of the primary polymers, and that an increase in the radiation dose slightly changed them. In general, it can be said that the results of the application of these polymer mixtures were important due to the improvement of some physical and thermal properties of polymers.

In another study [12], the effect of copper on a polypropylene mixture irradiated with gamma radiation containing a crosslinking agent was determined. The main conclusion of this study was the significant support that copper provides to the creation of a three-dimensional network in polypropylene mixtures during exposure to gamma radiation. Copper in the polypropylene structure accelerates the formation of free radicals in polypropylene, which contributed to the creation of a cross-linked structure. The results of the gel test (60.65%), the melt flow index (MFI) test and rheological analysis showed that the cross-linked

the structure obtained in the presence of copper was more pronounced at lower temperatures

radiation levels (20 kGy). Gamma radiation has a significant effect on the modification and improvement of polymer materials [13-19]. After radiation exposure, the polymers were more resistant to chemical reactions, since there were no ingredients left to react with. Gamma-ray-treated polymers can be used over a wider temperature range for particularly complex applications such as automotive, foil packaging, electrical insulation, tissue engineering, sterilization of medical devices, biomedical and nuclear applications, and more.

In [20], samples of polyvinylidene fluoride (PVDF) (fluoroplast-2M) and PVDF graphitized and filled with carbon fibers (CFs) of 15 wt were studied.% made in the form of cylinders with a friction surface area of 1 cm2 by molding under pressure from 100 to 120 MPa and at a temperature from 190 to 210 ° C. The radiation modification of the friction surface of the samples was carried out by emitting accelerated electrons with an energy of 1.0 MeV generated by the ELV-4 accelerator. The SHIMADZU Auto graph AGS-1 kNX test machine was used as a friction force measuring device. The pressure on the sample calculated from the contour of the contact field was 2.5 MPa. The wear tests lasted 56 hours, and the friction path was 10,000 m. The coefficients of friction on steel did not change significantly and were in the range of 0.12–0.15 regardless of the radiation dose. It was found that for a pure polymer, the dependence of the wear intensity on the absorbed dose is clearly pronounced, and the wear resistance deteriorates. For the composition with CFs, an increase in wear resistance was obtained by two times, compared with samples made of pure polymer.

The purpose of our work was to determine the micromechanical properties, friction coefficients without lubrication and in the presence of lubricant and mass loss of samples of radiation-modified and coke-filled fluoropolymers paired with a 40Kh steel counterplate in comparison with the reference material, polytetrafluoroethylene (PTFE) (fluoroplast F-4)

2 Materials and research methods

Experiments were performed on samples of PTFE fluoropolymers (1), radiation-modified (PTFE-RM) (2), irradiation mode - A, (3), PTFE-RM irradiation mode - B and PTFE coke filled with a coke content of 20% (F4K20) (4), made in the form of discs with a 40 mm dimeter, 8 mm high, shown in Fig. 1. Micromechanical studies were performed on the Nanoscan-4D device. A diamond triangular Berkovich pyramid was used for indentation. The maximum loading force was 10 mN. According to the load-unloading diagrams, the indenter immersion depth, microhardness HV, modulus of elasticity, E, elastic deformation work We, plastic deformation work, Wp, and other indicators were determined. Tribotechnical tests were performed on a friction machine with a vertical axis of rotation of the spindle according to the scheme: "the end of the annular surface of the counter–flange sleeve (steel 40X) is a plane (the end of the disk of a fluoropolymer sample)." The moment of friction and pressure on the samples were determined using strain gauges mounted on elastic beams placed on a friction machine in continuous mode. The processing of the end face of the steel counterbase was carried out on silicon carbide sandpaper with a grain size of P180, P600, P1200. For lubrication, hydraulic oil MGE-10 A was poured into an oil bath mounted on the slide table of the friction machine.

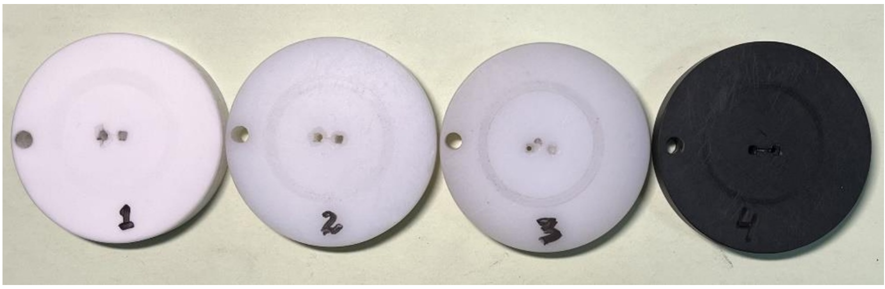


Fig. 1. Samples of fluoropolymers: 1 - PTFE, 2 –PTFE-RM (A), 3 –PTFE- RM (B), 4 - F4K20

3 Results

Fig. 2 shows an optical image of the Berkovich pyramid imprint on the surface of the PTFE-RM (B) sample. To determine the average values of microhardness, modulus of elasticity and elastic plastic deformation, measurements were made at fifteen points and close readings in the depth of the imprint were taken into account. Figure 3 shows the load-unloading curves of the indenter for PTFE samples (Fig. 3, a) and PTFE-RM (B) (Fig. 3, b). Table 1 shows the average values of microhardness, modulus of elasticity, work to overcome elastic and plastic deformation and their total contribution.

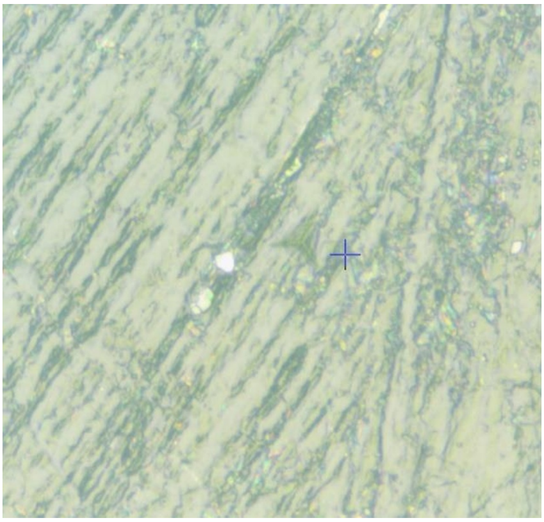
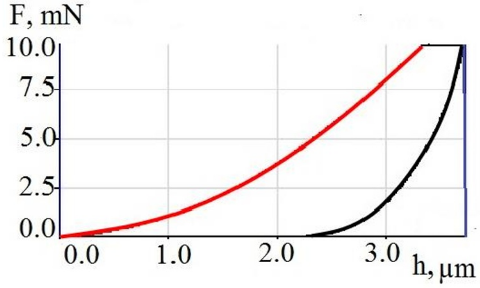
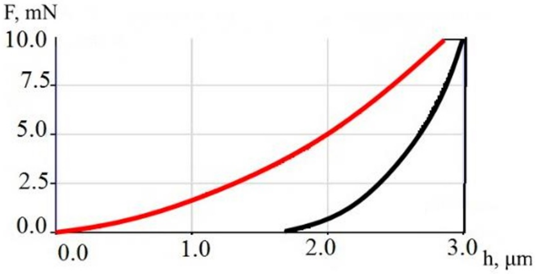


Fig. 2. Optical image of the Berkovich pyramid imprint RM PTFE (B)



a)



b)

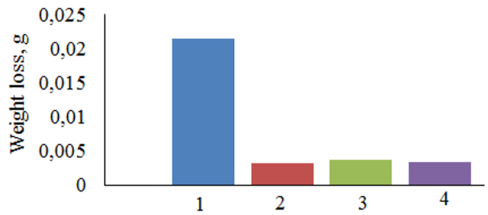
Fig. 3. Load-unloading curves for fluoropolymer samples: a-PTFE, b – PTFE-RM (B)

Table 1 Results of instrumental indentation of fluoropolymer samples

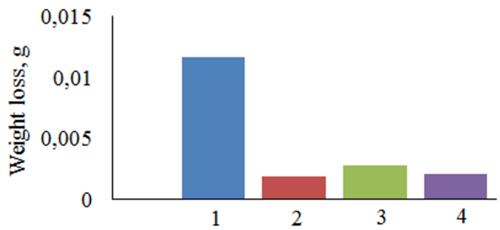
Sample number	Load, max, mN	HV	Modulus of elasticity, E, GPa	Elastic deformation work, We, mJ	The work of plastic deformation, Wp, mJ	The work of elastic plastic deformation, W, mJ
1	9,87	4,11	0,95	4,09	7,14	11,23

2	9,95	6,08	1,22	3,66	6,15	9,81
3	9,91	5,91	0,91	3,92	6,29	10,21
4	9,88	5,81	1,37	2,95	6,56	9,51

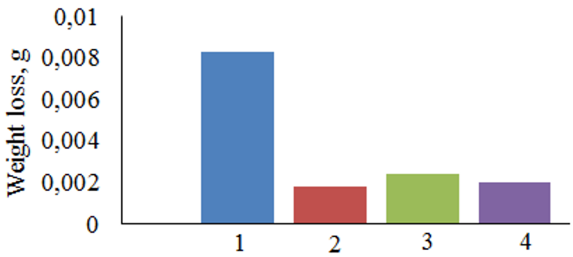
Figure 4 shows diagrams of the mass loss of samples during the wear test without lubricant in the "dry" friction mode, depending on the treatment of the end face with sandpaper of various grain sizes P 180 (a), P 600 (b) and P 1200 (c).PTFE-RM (A) samples had the lowest mass loss, followed by F4K20 and PTFE RM (B) samples. PTFE samples showed the worst results in weight loss. With a decrease in the height of the counter-tile irregularities, the mass loss of the samples decreased. So, if for PTFE samples this decrease occurred by 3 times, then for F4K20 samples by 16 times. The modified samples exceeded the PTFE reference samples in wear resistance 5-6 times when processing the counter-tile with sandpaper P 1200 and P 180, respectively.



a)



b)



c)

Fig. 4. Mass loss of fluoropolymer samples during friction without lubrication, depending on the treatment of the end face of the 40Kh steel counter-tile with sandpaper of various grain sizes: a- R 180, b– R 600, c – R 1200

Tests of samples using MGE-10A hydraulic oil showed that the PTFE standard was slightly inferior to F4K20, and PTFE – RM (B) and (A) were inferior in weight loss to the standard by 5-7%, respectively. In general, the radiation-modified and coke-filled samples showed high values of wear resistance under dry friction. In practice, all mechanisms and vehicles at the initial moment of movement operate under conditions of boundary friction in

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which it is possible to contact the surfaces of the parts directly with each other. In this case, the maximum wear of the contacting friction surfaces occurs. With an increase in sliding speeds, a significantly larger amount of lubricant enters the friction zone than at the initial moment of movement and the wear rate decreases. There are a number of open gears that do not provide lubrication. These include steel –polymer meshes. In this case, radiation-modified and coke-filled fluoropolymers will have a service life many times higher than the reference PTFE.

Fig. 5 shows the dependences of the friction coefficients on the test time for friction without lubricant (Fig. 5, a) and with MGE-10 A lubricant (Fig. 5, b). The highest values of the friction coefficient 0.25-0.27 were obtained for PTFE for friction without lubrication after processing the end surface of the steel counterplate with sandpaper P 180.

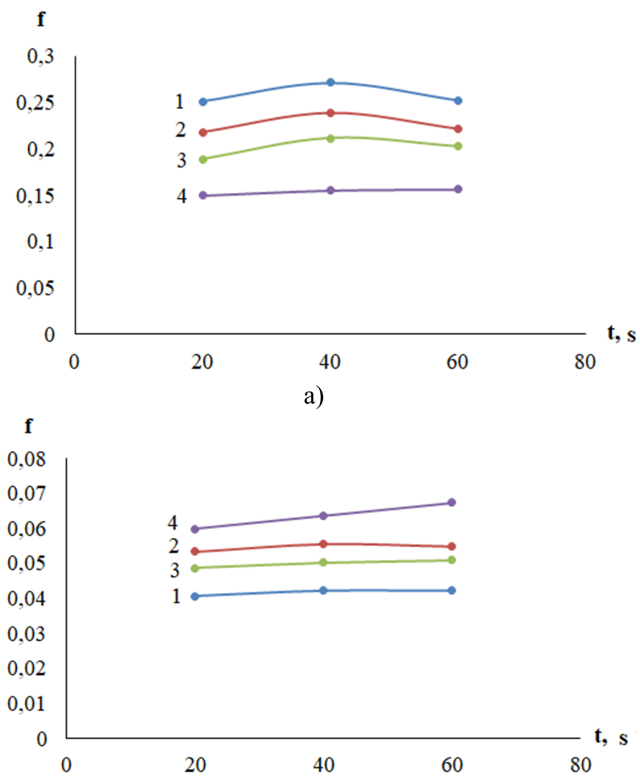

Fig. 5. Dependence of the friction coefficients of fluoropolymers during friction on steel 40Kh after processing with sandpaper P180: a-without lubrication, b- lubrication MGE–10 A

During friction with MGE – 10 A oil, the minimum values of the coefficient of friction were obtained from PTFE samples (Fig. 5, b). The minimum values of the coefficients of friction paired with a counter-tile after processing with sandpaper P 1200 under dry friction were obtained for PTFE-RM samples (B), followed by increasing samples of PTFE, F4K20 and PTFE - RM (A). In the presence of MGE -10 A oil, the minimum values of the friction coefficients were obtained by PTFE samples, followed in ascending order by the friction coefficients for samples F4K20, PTFE – RM (B), PTFE – RM (A).

4 Conclusion

1. The regularities of changes in the friction coefficients for samples of fluoropolymers in a friction pair with 40Kh steel, depending on the roughness of its surface at a constant sliding speed, are determined.

2. The evaluation of microhardness, modulus of elasticity and the work of elastic-plastic deformation under continuous indentation of a triangular Berkovich diamond pyramid was carried out. The minimum microhardness values were obtained for PTFE reference samples, and the microhardness of radiation-modified and coke-containing samples was 1.4-1.5 times higher than the standard.

3. Radiation-modified and gas-filled samples exceeded the standard PTFE samples 5-6 times in wear resistance when processing the counter-tile with sandpaper P 1200 and P 180, respectively.

References

1. J. Bijwe, Nidhi, Industrial Lubrication and Tribology **59**, 156–165 (2007). https://doi.org/10.1108/00368790710753545.
2. A. Charfi, S. Neili, M. Kharrat, M. Dammak, Journal of Thermoplastic Composite Materials **34**, 1639–1653 (2021). https://doi.org/10.1177/0892705719875203.
3. M. Trabelsi, M. Kharrat, M. Dammak, Transactions of the Indian Institute of Metals **69**, 1119–1128 (2016). https://doi.org/10.1007/s12666-015-0666-x.
4. B. Jongsomjit, J. Panpranot, P. Praserthdam, Materials Letters **61**, 1376–1379 (2007) https://doi.org/10.1016/j.matlet.2006.07.034.
5. B. Ben Difallah, P.H. Cornuault, M. Kharrat, M. Dammak, G. Monteil, Journal of Tribology **142**, 051901 (2020). https://doi.org/10.1115/1.4045804.
6. Y. Shang, Y. Zhao, Y. Liu, Y. Zhu, Z. Jiang, H. Zhang, High Performance Polymers **30**, 153–160 (2018). https://doi.org/10.1177/0954008316685410.
7. E. Basavaraj, B. Ramaraj, Siddaramaiah, High Performance Polymers **24**, 616–624 (2012). https://doi.org/10.1177/0954008312446765.
8. Y. Shang, X. Wu, Y. Liu, Z. Jiang, Z. Wang, Z. Jiang, H. Zhang, Preparation of PEEK/MWCNTs Composites with Excellent Mechanical and Tribological Properties. High Performance Polymers **31**, 43–50 (2019). https://doi.org/10.1177/0954008317750726.
9. K. Makuuchi, S. Cheng, Radiation Processing of Polymer Materials and Its Industrial Applications; Wiley: Hoboken, NJ, USA, 2012; p. 415. DOI:10.1002/9781118162798.
10. D. Gheysari, A. Behjat, M. Haji-Saeid, The effect of high-energy electron beam on mechanical and thermal properties of LDPE and HDPE. European Polymer Journal **37**, 295–302 (2001). https://doi.org/10.1016/S0014-3057(00)00122-1.
11. M. Sirin, M.S. Zeybek, K. Sirin, Y. Abali Effect of gamma irradiation on the thermal and mechanical behaviour of polypropylene and polyethylene blends. Radiation Physics and Chemistry **194**, 110034 (2022). https://doi.org/10.1016/j.radphyschem.2022.110034.
12. T.H. Yang, Y.C. Cheng, Y.P. Wu, B. Yu, T. Huang, H. Yu, M.F. Zhu, Enhanced crosslinking of polypropylene in gammairradiation via Copper (II) doping. Radiation Physics and Chemistry **194**, 110042 (2022) https://doi.org/10.1016/j.radphyschem.2022.110042.
13. A.T. Naikwadi, B.K. Sharma, K.D. Bhatt, P.A. Mahanwar, Frontiers in Chemistry **10**,

837111 (2022). https://doi.org/10.3389/fchem.2022.837111.

14. A.C. Abraham, M.A. Czayka, M.R. Fisch Electron beam irradiations of polypropylene syringe barrels and the resulting physical and chemical property changes. Radiation Physics and Chemistry **79**, 83–92 (2010). https://doi.org/10.1016/j.radphyschem.2009.08.027.
15. A. Ashfaq, M.C. Clochard, X. Coqueret, C. Dispenza, M.S. Driscoll, P. Ulański, M. Al-Sheikhly, Polymers **12**, 2877 (2020). https://doi.org/10.3390/polym12122877.
16. D.H. Han, S.H. Shin, S. Petrov, Radiation Physics and Chemistry **69**, 239–244 (2004) https://doi.org/10.1016/S0969-806X(03)00458-4.
17. H.T. Wang, H.Q. Jiang, R.F. Shen, X.J. Ding, C. Zhang, L.F. Li, J.Y. Li, Nuclear Science and Techniques **29,** 87 (2018). https://doi.org/10.1007/s41365-018-0424-y.
18. J. Hu, X. Zhao, J. Xie, Y. Liu, S. Sun, Polymer Engineering and Science **62**, 1756–1763 (2022)
19. https://doi.org/10.1002/pen.25961.
20. M. Okuhara, R. Nomura, Y. Nishi, Journal of the Japan Institute of Metals and Materials **80**, 360–364 (2016).
21. V. P. Selkin, S. V. Kopylov Journal of Friction and Wear **40**, 116–119 (2019). https://doi.org/10.3103/S1068366619020119.