http://doi.org/10.32864/polymmattech-2024-10-4-20-32

УДК 678.073:661.481

ЗАКОНОМЕРНОСТИ ФОРМИРОВАНИЯ ТРИБОСЛОЯ И СОПРОТИВЛЕНИЕ ИЗНАШИВАНИЮ КОМПОЗИТОВ НА ОСНОВЕ СУПЕРКОНСТРУКЦИОННОГО ТЕРМОПЛАСТА ПОЛИЭФИРСУЛЬФОНА

Д. Г. БУСЛОВИЧ[1], ЧАНЦЗЮНЬ ХЭ[2], С. В. ПАНИН[1,2+], Л. А. КОРНИЕНКО[1], И. С. ШИЛЬКО

[1]Институт физики прочности и материаловедения СО РАН, пр-т Академический, 2/4, 634055, г. Томск, Россия
[2]Национальный исследовательский Томский политехнический университет, пр-т Ленина, 30, 634050, г. Томск, Россия
[3]Институт механики металлополимерных систем имени В. А. Белого НАН Беларуси, ул. Кирова, 32а, 246050, г. Гомель, Беларусь

Цель работы — повысить трибологические (прежде всего износостойкость) свойства в условиях линейного трибоконтакта композитов на основе полиэфирсульфона (ПЭС) путем армирования углеродными волокнами (УВ) при варьировании их содержания; установить роль условий трибонагружения на формирование и эволюцию трибослоя, как ключевого фактора, определяющего сопротивление изнашиванию.

Проведены исследования трибологических свойств в условиях линейного трибоконтакта (схема «вал–колодка») в металло- и керамо-полимерном трибосопряжении композитов на основе ПЭС, армированных УВ с аспектным соотношением, равным 14–250, при варьировании их содержания 10–30 мас.%. Показано, что даже при использовании неантифрикционного полимера ПЭС в качестве матричного материала с высоким коэффициентом трения за счет реализации механизма формирования трибослоя может быть достигнуто многократное повышение сопротивления изнашиванию. Под трибослоем авторы подразумевают армированный фрагментированными УВ слой перемешивания толщиной до нескольких микрометров на основе полимерной матрицы, уплотненный и отшлифованный в результате многократного скольжения шероховатого контртела. По данным электронной микроскопии толщина трибослоя может составлять 2–7 мкм, где верхняя оценка определяется диаметром УВ, использованных для наполнения ПЭС. Показаны условия, при которых в линейном контакте происходит формирование трибослоя (из продуктов изнашивания): трехстадийный характер изменения коэффициента трения f во времени, когда на первой стадии (стадии приработки) f резко возрастает до величины 0,4–0,5, в то время как на второй плавно снижается до 0,1–0,2. Далее, если величина f не меняется, можно утверждать, что сформированный трибослой закрепился и выполняет свою функциональную роль. Определены оптимальный состав, размер наполнителя (УВ), тип сопряжения, формирующие высокие антифрикционные свойства композитов на основе суперконструкционного термопласта ПЭС.

Ключевые слова: полиэфирсульфон, углеродные волокна, физико-механические свойства, коэффициент трения, интенсивность изнашивания.

PATTERNS OF TRIBOLAYER FORMATION AND WEAR RESISTANCE OF COMPOSITES BASED ON HIGH-PERFORMANCE POLYETHERSULFONE

D. G. BUSLOVICH[1], CHANGJUN HE[2], S. V. PANIN[1, 2+], L. A. KORNIENKO[1], I. S. SHILKO[3]

[1]Institute of Strength Physics and Materials Science of Siberian Branch of Russian Academy of Sciences, Ave. Akademicheskiy, 2/4, 634055, Tomsk, Russia

[+]Автор, с которым следует вести переписку. E-mail: svp@ispms.ru

[2]National Research Tomsk Polytechnic University, Lenin Ave., 30, 634050, Tomsk, Russia
[3]V. A. Belyi Metal-Polymer Research Institute of National Academy of Sciences of Belarus, Kirov St., 32a, 246050, Gomel, Belarus

The aim of the work is to improve the tribological (primarily wear resistance) properties under conditions of linear tribocontact of composites based on PES by reinforcing with CF while varying their content; to establish the role of triboloading conditions on the formation and evolution of the tribolayer, as a key factor determining wear resistance.

The tribological properties were studied under conditions of linear tribocontact (the "bock-on-ring" scheme) in metal- and ceramic-polymer tribological mating of PES-based composites, reinforced with short carbon fibers (CF) with an aspect ratio of AR = 14-250 with their content of 10–30 wt.%. It was shown that even when using (non-antifriction) PES as a matrix material with a high friction coefficient, a multiple increase in wear resistance can be achieved due to the implementation of the tribolayer formation mechanism. By the tribolayer the authors mean a layer of mixing reinforced with fragmented SCFs up to several microns thick based on a polymer matrix, compacted and polished due to multiple sliding of a rough counterface. According to electron microscopy, the thickness of the tribolayer can be 2–7 μm, where the upper estimate is determined by the diameter of the CFs used to fill the PES. The conditions are proposed according to which the formation of a tribolayer from wear products occurs during linear tribocontact: a three-stage pattern of the change in time f, when at the first stage (stage of running-in) f sharply increases to a value of 0.4–0.5, while at the second it smoothly decreases to 0.1–0.2. Further, if the value of f does not change, it can be stated that the formed tribolayer has been adhered and performs its functional role. The optimal compositions, filler size (CF), and type of rubbing that form high antifriction properties of composites based on high-performance PES are determined.

Keywords: polyethersulfone (PES), carbon fibers (CF), physical and mechanical properties, friction coefficient, wear rate.

Поступила в редакцию 05.11.2024

Образец цитирования:

Буслович Д. Г., Хэ Чанцзюнь, Панин С. В., Корниенко Л. А., Шилько И. С. Закономерности формирования трибослоя и сопротивление изнашиванию композитов на основе суперконструкционного термопласта полиэфирсульфона // Полимерные материалы и технологии. 2024. Т. 10, № 4. С. 20–32. http://doi.org/10.32864/polymmattech-2024-10-4-20-32

Citation sample:

Buslovich D. G., Khe Chantszyun', Panin S. V., Kornienko L. A., Shil'ko I. S. Zakonomernosti formirovaniya tribosloya i soprotivlenie iznashivaniyu kompozitov na osnove superkonstruktsionnogo termoplasta poliefirsul'fona [Patterns of tribolayer formation and wear resistance of composites based on high-performance polyethersulfone]. *Polimernye materialy i tekhnologii* [Polymer Materials and Technologies], 2024, vol. 10, no. 4, pp. 20–32. http://doi.org/10.32864/polymmattech-2024-10-4-20-32

Литература

1. Yu L., Zhao D., Wang W. Mechanical properties and long-term durability of recycled polysulfone plastic // Waste Management, 2019, vol. 84, pp. 402–412. doi: 10.1016/j.wasman.2018.11.025

2. Chukov D., Nematulloev S., Zadorozhnyy M., Tcherdyntsev V., Stepashkin A., Zherebtsov D. Structure, Mechanical and Thermal Properties of Polyphenylene Sulfide and Polysulfone Impregnated Carbon Fiber Composites // Polymers, 2019, vol. 11. doi: 10.3390/polym11040684
3. Krasnov A. P., Shaposhnikova V. V., Salazkin S. N., Askadskii A. A., Goroshkov M. V., Naumkin A. V. Effect of Chemical Structures of Heat-Resistant Tribostable Thermoplastics on Their Tribological Properties: Establishing a General Relationship // INEOS OPEN, 2019, vol. 2, no. 3, pp. 68–77. doi: 10.32931/io1911r
4. Mamah S. C., Goh P. S., Ismail A. F., Suzaimi N. D., Yogarathinam L. T., Raji Y. O., El-badawy T. H. Recent development in modification of polysulfone membrane for water treatment application // Journal of Water Process Engineering, 2021, vol. 40. doi: 10.1016/j.jwpe.2020.101835
5. Unal H., Mimaroglu A., Demir Z. Tribological Performance of POM, PTFE and PSU Composites Used in Electrical Engineering Applications // International Journal of Polymeric Materials, 2010, vol. 59, is. 10, pp. 808–817. doi: 10.1080/00914037.2010.483220
6. Zuo Z., Song L., Yang Y. Tribological behavior of polyethersulfone-reinforced polytetrafluoroethylene composite under dry sliding condition // Tribology International, 2015, vol. 86, pp. 17–27. doi: 10.1016/j.triboint.2015.01.019
7. Bijwe J., Rajesh J. J., Jeyakumar A., Ghosh A. K. A study of the role of solid lubricant and fibrous reinforcement in modifying the wear performance of polyethersulphone // Journal of Synthetic Lubrication, 2000, vol. 17, is. 2, pp. 99–107. doi: 10.1002/jsl.3000170202
8. Yan S., Yang Y., Song L., Qi X., Zuo Z., Xue Y. Tribological property of 3-aminopropyltriethoxysilane-graphite oxide nanosheets reinforced polyethersulfone composite under drying sliding condition // Tribology International, 2016, vol. 103, pp. 316–330. doi: 10.1016/j.triboint.2016.07.016
9. Hua C., Zhao S., Lin L., Schlarb A. K. Tribological performance of a polyethersulfone (PESU)-based nanocomposite with potential surface changes of the metallic counterbody // Applied Surface Science, 2023, vol. 636. doi: 10.1016/j.apsusc.2023.157850
10. Harshavardhan B., Ravishankar R., Suresha B., Srinivas S., Dixit U. Arun C. Influence of short carbon fiber content on thermal properties of polyethersulfone composites // Materials Today Proceedings, 2021, vol. 43, pp. 1268–1275. doi: 10.1016/j.matpr.2020.08.769
11. Laban O., Pearce G., Zhang J., Islam M. S., Djukic L. P. A comparative study of the cryogenic performance of CFRP composites with polyethersulfone/epoxy blends and electrospun polyethersulfone interleaves // Composites Part A: Applied Science and Manufacturing, 2024, vol. 178. doi: 10.1016/j.compositesa.2023.108000
12. Panin S. V., Alexenko V. O., Buslovich D. G. High Performance Polymer Composites: A Role of Transfer Films in Ensuring Tribological Properties—A Review // Polymers, 2022, vol. 14, is. 5. doi: 10.3390/polym14050975
13. Sharma M., Bijwe J. Influence of fiber–matrix adhesion and operating parameters on sliding wear performance of carbon fabric polyethersulphone composites // Wear, 2011, vol. 271, is. 11-12, pp. 2919–2927. doi: 10.1016/j.wear.2011.06.012
14. Duan Y., Cong P., Liu X., Li T. Comparative Study of Tribological Properties of Polyphenylene Sulfide (PPS), Polyethersulfone (PES), and Polysulfone (PSU) // Journal of Macromolecular Science, Part B Physics, 2009, vol. 48, is. 2, pp. 269–281. doi: 10.1080/00222340802679474
15. Feng C., Guo Y., Yu Z., Chen K., Wang D., Li X., Luo Y., Wang Q., Zhang D. Tribological properties of PEEK composites reinforced by MoS_2 modified carbon fiber and nano SiO_2. // Tribology International, 2023, vol. 181. doi: 10.1016/j.triboint.2023.108315
16. Gebhard A., Jim B. C. Formation, stability and degradation of transfer films formed by polyphenylene sulfide (PPS) and its composites in dry sliding against steel // Wear, 2022, vol. 500-501. doi: 10.1016/j.wear.2022.204343
17. Chen B., Yang B., Tong Y., Dong W., Li J., Qiu S. Enhanced tribological properties of polyimide composite with carbon fiber/graphitic-carbon nitride nanosheets // Journal of Applied Polymer Science, 2023, vol. 140, is. 35. doi: 10.1002/app.54360
18. Zhao Z.-K., Du S.-S., Li F., Xiao H.-M., Li Y.-Q., Zhang W.-G., Hu N., Fu S.-Y. Mechanical and tribological properties of short glass fiber and short carbon fiber reinforced polyethersulfone composites: A comparative study // Composites Communications, 2018, vol. 8, pp. 1–6. doi: 10.1016/j.coco.2018.02.001
19. Panin S. V., Luo J., Buslovich D. G., Alexenko V. O., Kornienko L. A., Byakov A. V., Paimushin V. N., Shugurov A. R. Role of Testing Conditions in Formation of Tribological Layers at Line Contacts of Antifriction CF-Reinforced PI- and PEI-Based Composites // Molecules, 2022, vol. 27, is. 19. doi: 10.3390/molecules27196376

References

1. Yu L., Zhao D., Wang W. Mechanical properties and long-term durability of recycled polysulfone plastic. *Waste Management*, 2019, vol. 84, pp. 402–412. doi: 10.1016/j.wasman.2018.11.025
2. Chukov D., Nematulloev S., Zadorozhnyy M., Tcherdyntsev V., Stepashkin A., Zherebtsov D. Structure, Mechanical and Thermal Properties of Polyphenylene Sulfide and Polysulfone Impregnated Carbon Fiber Composites. *Polymers*, 2019, vol. 11. doi: 10.3390/polym11040684
3. Krasnov A. P., Shaposhnikova V. V., Salazkin S. N., Askadskii A. A., Goroshkov M. V., Naumkin A. V. Effect of Chemical Structures of Heat-Resistant Tribostable Thermoplastics on Their Tribological Properties: Establishing a General Relationship. *INEOS OPEN*, 2019, vol. 2, no. 3, pp. 68–77. doi: 10.32931/io1911r
4. Mamah S. C., Goh P. S., Ismail A. F., Suzaimi N. D., Yogarathinam L. T., Raji Y. O., El-badawy T. H. Recent development in modification of polysulfone membrane for water treatment application. *Journal of Water Process Engineering*, 2021, vol. 40. doi: 10.1016/j.jwpe.2020.101835
5. Unal H., Mimaroglu A., Demir Z. Tribological Performance of POM, PTFE and PSU Composites Used in Electrical Engineering Applications. *International Journal of Polymeric Materials*, 2010, vol. 59, is. 10, pp. 808–817. doi: 10.1080/00914037.2010.483220
6. Zuo Z., Song L., Yang Y. Tribological behavior of polyethersulfone-reinforced polytetrafluoroethylene composite under dry sliding condition. *Tribology International*, 2015, vol. 86, pp. 17–27. doi: 10.1016/j.triboint.2015.01.019
7. Bijwe J., Rajesh J. J., Jeyakumar A., Ghosh A. K. A study of the role of solid lubricant and fibrous reinforcement in modifying the wear performance of polyethersulphone. *Journal of Synthetic Lubrication*, 2000, vol. 17, is. 2, pp. 99–107. doi: 10.1002/jsl.3000170202
8. Yan S., Yang Y., Song L., Qi X., Zuo Z., Xue Y. Tribological property of 3-aminopropyltriethoxysilane-graphite oxide nanosheets reinforced polyethersulfone composite under drying sliding condition. *Tribology International*, 2016, vol. 103, pp. 316–330. doi: 10.1016/j.triboint.2016.07.016
9. Hua C., Zhao S., Lin L., Schlarb A. K. Tribological performance of a polyethersulfone (PESU)-based nanocomposite with potential surface changes of the metallic counterbody. *Applied Surface Science*, 2023, vol. 636. doi: 10.1016/j.apsusc.2023.157850
10. Harshavardhan B., Ravishankar R., Suresha B., Srinivas S., Dixit U. Arun C. Influence of short carbon fiber content on thermal properties of polyethersulfone composites. Materials Today Proceedings, 2021, vol. 43, pp. 1268–1275. doi: 10.1016/j.matpr.2020.08.769
11. Laban O., Pearce G., Zhang J., Islam M. S., Djukic L. P. A comparative study of the cryogenic performance of CFRP composites with polyethersulfone/epoxy blends and electrospun polyethersulfone interleaves. *Composites Part A: Applied Science and Manufacturing*, 2024, vol. 178. doi: 10.1016/j.compositesa.2023.108000
12. Panin S. V., Alexenko V. O., Buslovich D. G. High Performance Polymer Composites: A Role of Transfer Films in Ensuring Tribological

Properties—A Review. *Polymers*, 2022, vol. 14, is. 5. doi: 10.3390/polym14050975
13. Sharma M., Bijwe J. Influence of fiber–matrix adhesion and operating parameters on sliding wear performance of carbon fabric polyethersulphone composites. *Wear*, 2011, vol. 271, is. 11-12, pp. 2919–2927. doi: 10.1016/j.wear.2011.06.012
14. Duan Y., Cong P., Liu X., Li T. Comparative Study of Tribological Properties of Polyphenylene Sulfide (PPS), Polyethersulfone (PES), and Polysulfone (PSU). *Journal of Macromolecular Science, Part B Physics*, 2009, vol. 48, is. 2, pp. 269–281. doi: 10.1080/00222340802679474
15. Feng C., Guo Y., Yu Z., Chen K., Wang D., Li X., Luo Y., Wang Q., Zhang D. Tribological properties of PEEK composites reinforced by MoS_2 modified carbon fiber and nano SiO_2. *Tribology International*, 2023, vol. 181. doi: 10.1016/j.triboint.2023.108315
16. Gebhard A., Jim B. C. Formation, stability and degradation of transfer films formed by polyphenylene sulfide (PPS) and its composites in dry sliding against steel. *Wear*, 2022, vol. 500-501. doi: 10.1016/j.wear.2022.204343
17. Chen B., Yang B., Tong Y., Dong W., Li J., Qiu S. Enhanced tribological properties of polyimide composite with carbon fiber/graphitic-carbon nitride nanosheets. *Journal of Applied Polymer Science*, 2023, vol. 140, is. 35. doi: 10.1002/app.54360
18. Zhao Z.-K., Du S.-S., Li F., Xiao H.-M., Li Y.-Q., Zhang W.-G., Hu N., Fu S.-Y. Mechanical and tribological properties of short glass fiber and short carbon fiber reinforced polyethersulfone composites: A comparative study. *Composites Communications*, 2018, vol. 8, pp. 1–6. doi: 10.1016/j.coco.2018.02.001
19. Panin S. V., Luo J., Buslovich D. G., Alexenko V. O., Kornienko L. A., Byakov A. V., Paimushin V. N., Shugurov A. R. Role of Testing Conditions in Formation of Tribological Layers at Line Contacts of Antifriction CF-Reinforced PI- and PEI-Based Composites. *Molecules*, 2022, vol. 27, is. 19. doi: 10.3390/molecules27196376