ISSN 2079-1372 Problems of Tribology, V. 30, No 2/116-2025, 14-18

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2025-116-2-14-18

The influence of a binary alloy of the Al-Cr system on the tribological properties of ultra-high-molecular-weight polyethylene

O.I. Popil0009-0004-8770-2351**, A.-M.V. Tomina***0000-0001-5354-0674

Dniprovsk State Technical University, Kamyanske, Ukraine
E-mail: an.mtomina@gmail.com

Received: 10 March 2025: Revised 25 March 2025: Accept: 15 April 2025

Abstract

The work studied the influence of a liquid-quenched binary alloy of the Al-Cr system with a chromium content of 5 wt.% on the tribological properties of ultra-high-molecular-weight polyethylene under friction without lubrication according to the “disk-pad” scheme and with rigidly fixed abrasive particles. We established that the introduction of 5-30 wt.% this alloy leads to a decrease in the intensity of linear wear and the abrasive wear rate of ultra-high-molecular-weight polyethylene by 2.8 and 2 times, respectively. The improvement of these indicators is due to several factors. A solid filler (HV≈600 MPa) contributes to the strengthening of the surface layer of the material undergoing wear. On the other hand, this can be explained by the formation of a more strained Al-based solid solution lattice, since it is known that binary quenched from the liquid state aluminum-based alloys are characterized by a high degree of microstresses due to the significant difference in the sizes of Al-Cr atoms. A composite with a filler content of 20 wt.% has the best set of functional properties. We can recommend this material for the manufacture of tribotechnical (gears, sprockets, bushings, and plain bearings) and structural (rollers, gear wheels, and bearing housings) parts for agricultural machinery and the mining industry operating under conditions of impact-abrasive or fatigue wear.

Keywords: ultra-high-molecular-weight polyethylene, liquid-quenched binary Al-Cr alloy, dispersed filler, abrasive wear rate, linear wear intensity

Introduction

Working bodies and friction units of agricultural machinery and the mining industry lose their performance due to impact-abrasive or fatigue wear [1] influenced by mechanical loads in almost 80% of cases. One of the promising directions for increasing their wear resistance is using polymer composite materials (PCMs). Using PCMs instead of serial parts allows us to increase mobility, work productivity, and the period of stable operation of units, as well as reduce maintenance and repair costs [2].

Therefore, the development, research, and implementation of wear-resistant materials that can effectively withstand intense mechanical loads [3] is the current task of many domestic and foreign researchers. Another important advantage of using PCMs instead of metals and semi-finished products based on them is the reduction of the labor intensity of manufacturing and the cost of products by up to 6 and 5 times, respectively, even for products of complex configuration. Using high-performance technologies that contribute to saving resources helps achieve this [4].

Analysis of modern domestic and foreign literature shows that PCMs based on ultra-high-molecular-weight polyethylene (UHMWPE), modified with various powder (dispersed) fillers (FLs), are of considerable interest for these purposes. It has been proven that the introduction of graphene nanoplatelets, diabase [5], natural and crucible graphite, graphene oxide [6], iron particles [7], silicon carbide, carbon nanotubes [8], high-entropy and binary alloys [9, 10] allows obtaining materials with high thermal conductivity, hardness, stiffness, resistance to corrosion and wear, low coefficient of friction and minimal water absorption.

The purpose of the work

Considering the above, the work aims to study the influence of a powder filler, a binary alloy of the Al-Cr system, on the tribotechnical characteristics of polymer composite materials based on UHMWPE to increase their wear resistance under various friction conditions.

Objects and methods of research

We used commercial UHMWPE from Jiujiang Zhongke Xinxing New Material Co., Ltd. (China) to create new wear-resistant PCM compositions. UHMWPE is a unique polymer with high functional properties, including chemical inertness, high self-lubricating ability, resistance to corrosion, cavitation erosion, wear (15 times higher than carbon steel), and impact (even at cryogenic temperatures), rigidity, and low static and dynamic coefficients of friction [11]. The high technical characteristics of UHMWPE are associated with its molecular structure. UHMWPE has extremely long molecular chains, with a high molecular weight (5-5.5 million g/mol), which ensure the effective transfer of applied loads along the polymer base.

A dispersed (40-100 μm) liquid-quenched single-phase binary state alloy of the Al-Cr system with a chromium content of 5 wt.% was chosen as a filler. FLs of this type are characterized by high indicators of functional properties because of the high ($\Delta a/a \geq 2.5 \cdot 10^{-3}$) level of microstresses in the crystal lattice due to the significant difference in the atomic radii of aluminum (r_{Al}=0.142 nm) and chromium (r_{Cr}=0.128 nm) [12]. The formation of research samples from PCMs containing 5-30 wt.% FLs was performed by the compression pressing method [10]. We studied tribological properties of PCMs and UHMWPE under friction conditions without lubrication during rotational motion according to the "disk-pad" scheme in a pair with a steel cylindrical counterbody (steel 45, ø50 mm, hardness was 45-48 HRC, and surface roughness was R_a=0.32 μm) at a sliding speed of 1 m/s and a load of 1 MPa on the SMC-2 friction machine. We determined the abrasive wear ratio by rigidly fixed abrasive particles (dispersion was 100 μm) using a HECKERT experimental machine at a constant load of 10 N. The wear value of UHMWPE and PCMs based on it was determined by the gravimetric method using an analytical VLR-200 balance (accuracy was 10^{-5} g). Then, the results were converted into wear intensity and abrasion ratio using known methods.

The roughness of the samples on the R_a scale was measured after friction using a 170621 probe profilometer. High-quality, detailed images of the friction surfaces of the studied samples, including their texture, structural features, and microroughnesses, were obtained in reflected incident light using a BIOLAM-M binocular microscope. We determined the hardness of UHMWPE and PCMs on the Rockwell HRR scale (preliminary and total load was 98.1 N and 588.4 N, respectively) using a 2074 TPR device. We measured the microhardness of the binary alloy using a PMT-3M microhardness tester with a load of 5 g. X-ray studies of the FL were performed on a DRON-2.0 diffractometer in monochromatized K_α copper radiation along the lines (111) and (222) (Fig. 1).

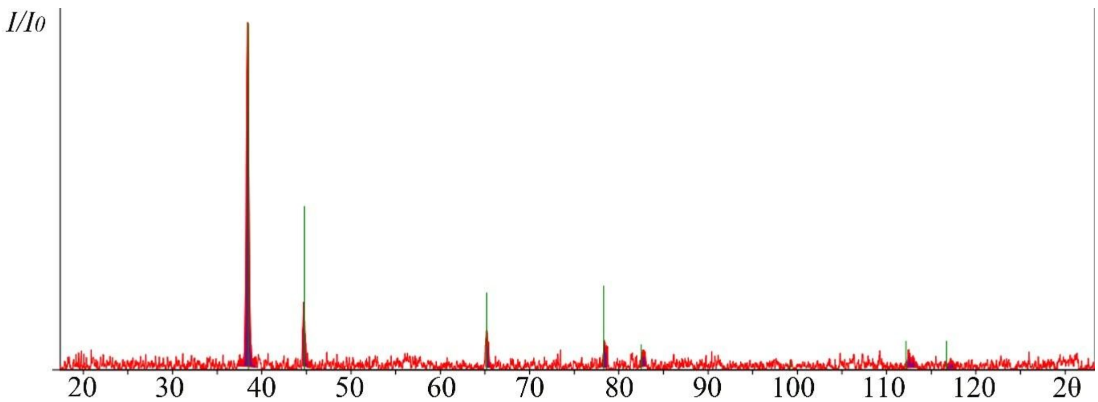


Fig. 1. Diffraction pattern of a liquid-quenched single-phase highly supersaturated fcc binary Al-5 wt.% Cr alloy

Results

We can see from Table 1 that introducing the FL leads to a decrease in the intensity of linear wear and the abrasive wear ratio of UHMWPE by 2.8 and 2 times, respectively. The increase in wear resistance of UHMWPE in both friction conditions is because solid FL particles (HV≈600 MPa) strengthen the surface layer, increasing its hardness by 1.5 times and resistance to mechanical stress. This, in turn, contributes to a uniform distribution of the applied load, a decrease in the depth of the ploughing furrows (roughness in both friction methods decreases by about 1.5 times), and local pressure concentration [13]. As a result, this contributes to a slowdown in the formation of microcracks (Fig. 2).

Table 1

Functional properties of UHMWPE and PCM based on it

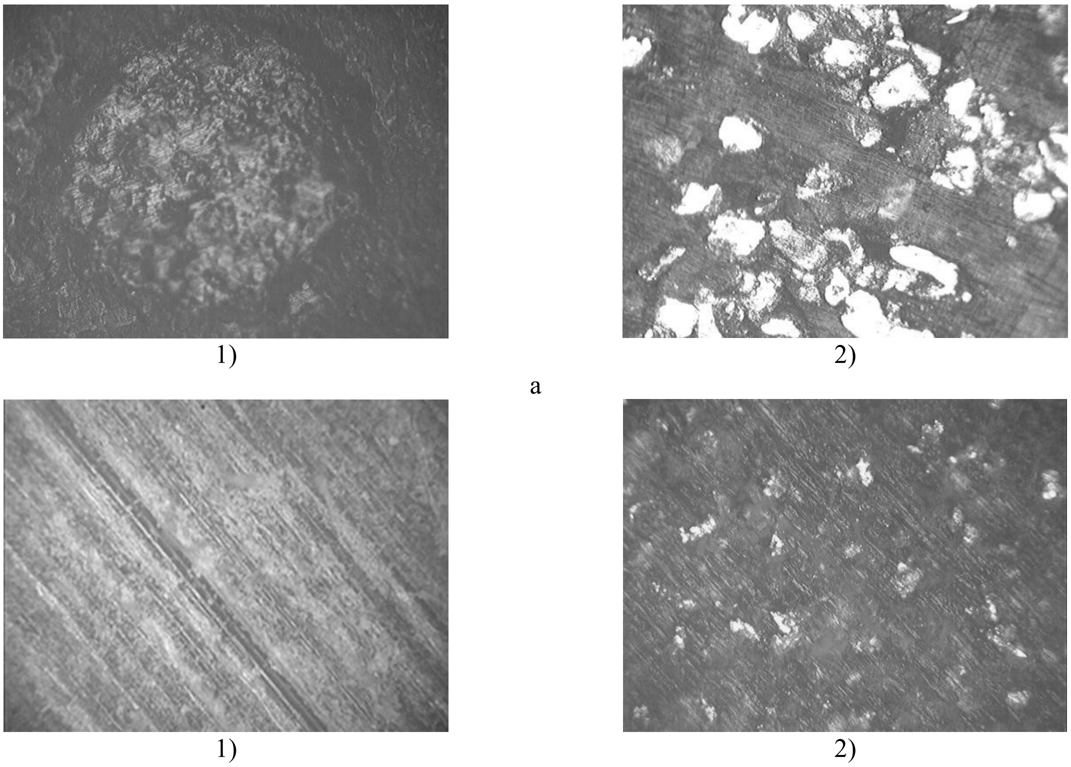
Indicator	Filler content, wt.%						
	0	5	10	15	20	25	30
linear wear intensity*, $I_h \cdot 10^{-7}$	15,8	11,2	8,7	6,9	5,7	6,8	8,1
abrasive wear rate*, V_i, mm^3/m	1,36	0,9	0,75	0,73	0,72	0,8	0,95
Hardness HRR, hardness units	32	38	41	45	48	46	44
Roughness of friction surfaces***, R_a, μm: - under friction conditions without lubrication - under the influence of rigidly fixed abrasive particles	2,14 2,57	1,90 2,11	1,72 1,97	1,51 1,92	1,45 1,87	1,63 1,97	1,85 2,24
Coefficient of friction, f	0,12	0,13	0,15	0,15	0,16	0,13	0,12

* average value from 3 experiments

**average value from 5 test cycles

***average value of at least 12 measurements

In addition, a harder FL in the composition of UHMWPE leads to an improvement in the adhesive and cohesive properties of the polymer, the formation of an "antifriction coating" on the steel counterbody, which reduces the intensity of the formation of adhesion zones with the steel counterbody (Fig. 2), and the formation of fragmented wear particles in the process of friction without lubrication. These facts are confirmed by a comparison of the morphology of the friction surfaces of pure UHMWPE (Fig. 2, 1) and PCM based on it (Fig. 2, 2) [14].



b

Fig. 2. Friction surfaces (×200) of pure UHWMPE (1) and polymer composite (2) based on it, containing 20 wt.% binary Al-Cr alloy according to the scheme under friction conditions without lubrication (a) and on rigidly attached abrasive particles (b)

On the other hand, forming a more ordered supramolecular structure can explain the increase in the functional properties of UHWMPE.

Worth noting that the improvement of the functional properties of UHWMPE is observed at 5–20 wt.% filler content. Further increase to 25–30 wt.% in UHWMPE leads to a deterioration of all indicators due to the increase in structural defects, which in turn are caused by the agglomeration of binary alloy particles, their uneven distribution in the volume of UHWMPE, and a decrease in the adhesive interaction at the "FL-UHWMPE" interface. Consequently, this causes the formation of weak zones (pores and voids), which reduce the hardness and strength of the PCM and also cause the intensification of wear processes under the influence of the applied load.

The increase in friction coefficient for all PCMs containing metallic FL in the composition is observed (Table 1). The fact that the solid particles of the Al-Cr alloy contribute to the formation of additional mechanical bonds with the steel counterbody, which increases the sliding resistance, can explain this [15].

Conclusions

Analysing the results of the study of the developed PCMs tribological properties showed that the introduction of 5-20 wt.% liquid-quenched binary Al-Cr alloy leads to an increase in wear resistance under conditions of friction without lubrication and the influence of abrasive particles by 2.8 and 2 times, respectively. The fact that harder FL particles strengthen the UHWMPE, as a result of which the friction surface more effectively counteracts destructive processes, can explain the improvement of these indicators. We can recommend PCMs with an effective FL content of 20 wt.% for the manufacture of working bodies (rollers, gears, and bearing housings) and friction units (gears, sprockets, bushings, and plain bearings) of agricultural machinery and the mining industry operating under conditions of impact-abrasive or fatigue wear.

References

1. I.M. Rybalko, R.S. Ryzhkov Management of abrasive wear of machine parts "Youth and Industry 4.0 in the 21st Century" Materials of the 20th International Youth Forum (April 04-05, 2024, Kharkiv). Kharkiv: SBTU, 2024. P.142.

2. A.S. Kobets Application of polymer composites in the agricultural industry. Monograph. Dnipro: Zhurfond, 2022. 356 p.

3. O.O. Skvortsov, O.O. Mikosianchyk Research of the wear resistance of electro-spark coatings under abrasive conditions. Problems of friction and wear. 2023. Vol.100, №3. P. 64-72.

4. M.S. Khimko, A.M. Khimko, P.G. Mnatsakanov, V.V. Klipachenko, R.O. Makarenko Wear resistance of polymer composite materials forplane spherical bearings. Problems of friction and wear. 2024. Vol.103, No.2. P. 29-42.

5. M. Skakov, M. Bayandinova, Y. Kozhakhmetov, B. Tuyakbaev Microstructure and corrosion resistance of composite based on ultra-high molecular weight polyethylene in acidic media. Coatings 2025. Vol. 15, No.1. P. 89; https://doi.org/10.3390/coatings15010089

6. A.Y. Adesina, M.F. Khan, M.U. Azam, M. Abdul Samad, A.A. Sorour, Characterization and corrosion resistance of ultra-high molecular weight polyethylene composite coatings reinforced with tungsten carbide particles in hydrochloric acid medium. Journal of Polymer Engineering. 2019. Vol. 39. P. 861–873.

7. J.F. M. Borges, O.M. Cintho, A. Camilo Júnior, M.D. Michel Ultra-high molecular weight polyethylene filled with iron by mechanical alloying. Revista delos. 2024. 17(61). e2660. https://doi.org/10.55905/rdelosv17.n61-098

8. T. Deplancke, O. Lame, S. Barrau, K. Ravi, F. Dalmas Impact of carbon nanotube prelocalization on the ultra-low electrical percolation threshold and on the mechanical behavior of sintered UHMWPE-based nanocomposites. Polymer. 2017. Vol. 111. P. 204–213.

9. V.F. Bashev, A.-M.V. Tomina, K.A. Mykyta, T.V. Kalinina, S.I. Riabtsev, O.I. Kushnerov The influence of a rapidly-quenched filler on the wear resistance of ultrahigh molecular weight polyethylene. Functional Materials. 2024. Vol.31, No.3. P. 387-390.

10. V.F. Bashev, S.V. Tomin, T.V. Kalinina, O.I. Kushnerov, N.P. Bondar Effect of binary Al-Ni alloy on the rate of abrasive wear of ultra-high molecular weight polyethylene. Functional Materials. 2024. Vol.31, No.4. P. 557–560.

11. J. Baena, J. Wu, Z. Peng, Wear performance of UHMWPE and reinforced UHMWPE composites in arthroplasty applications. A Review. Lubricants. 2015. Vol. 3, No.2. P. 413–436.

12. S.I. Mudryi, Yu. O Kulik, A.S. Yakymovych.X-ray structural analysis in materials science. teaching-methodical manual.-Ivan Franko National University of Lviv. Lviv-2017. 226 p.

13. A.-M.V. Tomina, Y.A. Yeriomina Studying the influence of HB-4 amorphous alloy on tribological properties of phenylone aromatic polyamide. Functional Materials. 2022. Vol.29, No.3. P. 388–392.

14. Ye. Yeriomina, A. Burya, T. Rybak Investigating the influence of fine-dispersed aluminum, nickel and titanium on the properties of phenylone. Scientific Journal of TNTU. Tern.: TNTU, 2019. Vol. 94. No. 2. P. 58–63.

15. O. Burya, Ye. Yeriomina, O. Lysenko, A. Konchits, A. Morozov, Polymer composites based on thermoplastic binders, Dnipro: Srednyak T. K. Press. 2019. 239 p.

Попіль О.І., Томіна А.-М.В. Вплив бінарного сплаву системи Al-Cr на трибологічні властивості надвисокомолекулярного поліетилену

У роботі досліджено вплив загартованого з рідини бінарного сплаву системи Al-Cr з відсотковим вмістом хрому 5 мас.% на трибологічні властивості надвисокомолекулярного поліетилену в умовах тертя без змащення за схемою «диск-колодка» та за жорсткозакріпленими частками абразиву. Встановлено, що введення цього сплаву у кількості 5-30 мас.% призводить до зменшення інтенсивності лінійного зношування та показника абразивного стирання надвисокомолекулярного поліетилену в 2,8 та 2 рази відповідно. Покращення цих показників зумовлене декількома чинниками. Введення твердого наповнювача з мікротвердістю близько HV≈600 МПа сприяє зміцненню поверхневого шару матеріалу, що, в свою чергу, збільшує його опір до механічного впливу та зменшує інтенсивність руйнування поліетилену в умовах тертя без змащення та за жорсткозакріпленими частками абразиву. З іншого боку, це можна пояснити формуванням більш напруженої решітки твердого розчину на основі Al, оскільки відомо, що загартовані з рідкого стану бінарні сплави на основі алюмінію характеризуються високим ступенем мікронапружень через значну різницю в розмірах атомів Al-Cr (rAl=0,142 нм та rCr=0,128 нм). Що стосується коефіцієнту тертя, введення бінарного сплаву системи Al-Cr до надвисокомолекулярного поліетилену призводить до його збільшення. Це обумовлено появою додаткових механічних зчеплень твердих часток наповнювача з сталевим контртілом, що в свою чергу, сприяє зростанню опору ковзанню. Найкращим комплексом функціональних властивостей характеризується композит з вмістом наповнювача 20 мас.%. Даний матеріал можна рекомендувати для виготовлення деталей триботехнічного (шестерні, зірочки, втулки та підшипники ковзання) і конструкційного (ролики, зубчасті колеса та корпуси підшипників) призначення сільськогосподарської техніки і гірничодобувної промисловості, що працюють в умовах ударно-абразивного або втомного зношування.

Ключові слова: надвисокомолекулярний поліетилен, загартований з рідини бінарний сплав Al-Cr, дисперсний наповнювач, показник абразивного стирання, інтенсивність лінійного зношування