UDC 620.891 DOI: 10.18372/0370-2197.2(111).21339

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EFFECT OF NANOCRYSTALLINE $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ ALLOY ON THE ABRASIVE WEAR RATE OF POLYETHERETHERKETONE AND ULTRA-HIGH-MOLECULAR WEIGHT POLYETHYLENE

This study investigated the effect of the content of a nanocrystalline magnetic alloy (at.%) with the composition $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ (Finemet class) on the abrasive wear index of polyetheretherketone and ultra-high molecular weight polyethylene. The tests were carried out under conditions involving rigidly fixed abrasive particles using a HECKERT machine; hardness and surface roughness parameters were also determined. It was found that introducing this alloy at 5–35 wt.% leads to a 2,9-fold increase in the wear resistance of polyetheretherketone and a 2-fold increase for ultra-high molecular weight polyethylene. The enhancement in wear resistance of the investigated metal-polymer composite materials is attributed to the fact that small (40–100 μm) hard particles of the $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ alloy (with a microhardness of approximately 15 000 MPa) hinder micro-cutting and microplastic deformation processes, thereby reducing the depth of ploughing grooves. This is also confirmed by a decrease in the surface roughness parameter (R_a) of polyetheretherketone by 2,9 times and ultra-high molecular weight polyethylene by 2,5 times. Increasing the filler content beyond 30 wt.% for polyetheretherketone and 35 wt.% for ultra-high molecular weight polyethylene leads to particle agglomeration, increased porosity, and a subsequent decline in the material's tribological performance. The developed metal-polymer composite materials are recommended for the manufacturing of working components and auxiliary units in modern machinery operating in aggressive abrasive environments.

Keywords: *polyetheretherketone, ultra-high molecular weight polyethylene, abrasive wear, nanocrystalline magnetic alloy $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$*

Introduction. One of the common causes of the loss of effective performance of working bodies (drums, coulters) and auxiliary units (bearings, bushings), equipped with serial parts of machines and mechanisms of sowing, tillage and root harvesting equipment, is the destruction of the surface due to the influence of an abrasive environment (particles of sand and soil, products of crop processing) [1]. This, in turn, results in significant financial costs, estimated at several million dollars per year, related not only to the replacement and repair of worn parts, but also to the reduced productivity of field cultivation [2].

An effective solution to this problem is the use of polymer composite materials based on thermoplastics, in particular based on polyetheretherketone (PEEK) and ultra-high molecular weight polyethylene (UHMWPE), which contain as fillers (Nps) binary alloys based on aluminum [3], micro- and nanoscale particles of silicon dioxide SiO_2 [4], zeolite, hydrogenated diamond-like carbon [5], nanodiamonds and nanoclay [6]. Their use allows not only to increase the service life of the equipment due to high abrasive wear resistance, but also to simultaneously reduce its mass, in the manufacture of working bodies, which, in turn, reduces the load on the soil, and, as a result, increases energy efficiency by reducing fuel consumption [7]. In particular, polymer composites based on PEEK and UHMWPE are widely used for manufacturing plain bearings and seals for tribological units of rolling mills, as well as bushings and guide elements for the seeding units of agricultural seed drills (such as the John Deere 1780 or KINZE 7600). These components operate under conditions of abrasive wear and moisture, with limited or no lubrication, thereby reducing maintenance costs and improving the reliability and durability of the equipment. Another important advantage of polymer composites is the possibility of obtaining products of complex geometric shape in one technological cycle and with a minimum amount of waste [8].

Considering the relevance of the mentioned problems, the aim of this work was to investigate the effect of the content of the nanocrystalline magnetic alloy $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ on the abrasive wear index of polyetheretherketone and ultra-high-molecular-weight polyethylene.

Materials and research methods. As polymer matrices, when creating new compositions of metal-polymer composite materials (MPCM), the following were used:

- Victrex® 150G PEEK (Victrex, UK) – is a semi-crystalline thermoplastic with a unique combination of functional properties, including resistance to organic and aquatic environments, high modulus of elasticity, tensile strength and hardness, which are preserved under the influence of elevated temperatures (≤523 K) [9].
- UHMWPE manufactured by Jiujiang Zhongke Xinxing New Material Co.,Ltd. (China) – linear semi-crystalline copolymer with high impact strength, high resistance to fatigue and dynamic loading, moisture, ultraviolet radiation and aggressive environments. This combination of unique technical characteristics provides it with a high molecular weight of $5–5,5·10^6$ g/mol [3, 8].

The nanocrystalline magnetic alloy of the composition $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$, which performs the function of a highly effective solid filler with a nanocrystal size of ~ 10 nm, was chosen as the filler. The obtained nanocrystals are the product of crystallization of the initial amorphous phase obtained by rapid melt quenching by the splat-quenching method. During heat treatment at a temperature of 803–823 K, this amorphous phase splits into a mixture of: a solid solution of silicon in BCC iron (α-Fe(Si))+ultrahard Fe_2B boride with a microhardness of ~ 15000 MPa. This mixture is also a kind of composite in which solid nanocrystals of the Fe_2B phase are evenly distributed in the plastic matrix of BCC iron.

The production of samples of metallopolymer composite materials that contained 5–35 wt% of the nanocrystalline magnetic alloy $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$, was performed by compression pressing according to the modes given in works [3, 10] without additional use of ferromagnetic elements. The indicator of abrasive abrasion of pure polymers and MPCM based on them was determined using a HECKERT tribometer, and an abrasive paper with a dispersion of 100 μm was used as a rigidly fastened abrasive). Determination of the hardness of pure polymers and MPCM based on them was carried out according to the Rockwell method using 2074 TPR hardness tester. The HRK scale was used for PEEK, and the HRR scale was used for UHMWPE. This is due to significant differences in the mechanical properties of experimental polymers, in particular their stiffness and deformation resistance. Evaluation of the morphology of friction surfaces was carried out by a qualitative and quantitative method, using the BIOLAM-M microscope and the profilometer (model 170621) based on the R_a parameter.

Analysis of results and discussion. The data presented in Fig. 1 indicate that the addition of 5–35 wt.% of the nanocrystalline magnetic alloy $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ results in a reduction of the abrasive wear index of PEEK and UHMWPE by 2,9 and

2,0 times, respectively. The lowest wear values are achieved at a nanofiller content of 25 wt.% for PEEK and 30 wt.% for UHMWPE.

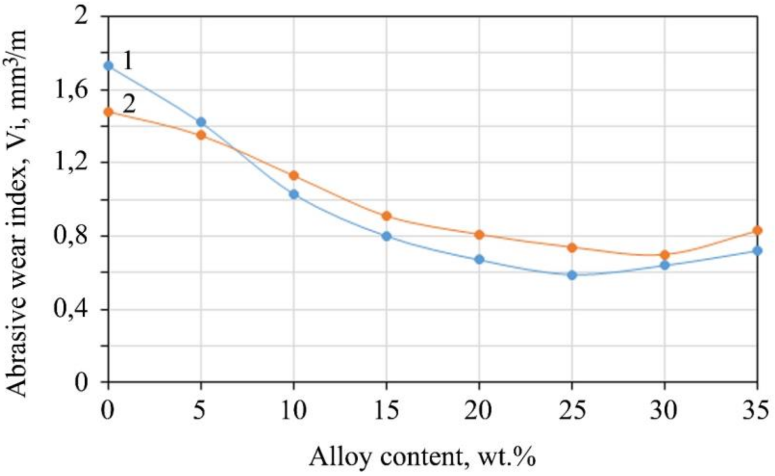

Fig.1. Effect of $Fe_{71,1}Si_{18,6}B_{6,3}Nb_3Cu_1$ alloy on the abrasive wear index (V_i, mm^3/m*) of PEEK (1) and UHMWPE (2) *(*values represent averages of three test cycles)*

The increase in the wear resistance of PEEK- and UHMWPE-based MPCMs under the action of fixed abrasive particles is attributed to fine particles of a mixed phase consisting of body-centered cubic (BCC) iron and the superhard Fe_2B, boride strengthen the polymer matrix and hinder the development of microcutting and microplastic deformation processes on the surface of the tested samples. This is confirmed by an approximately 1,5-fold increase in the hardness of the MPCM (see Fig. 2).

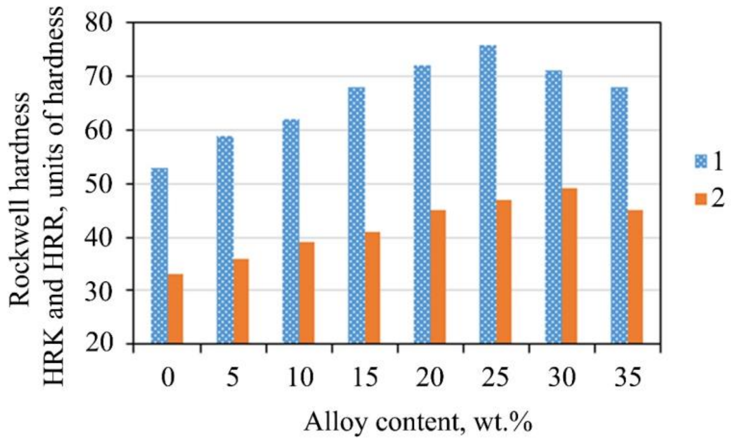

Fig. 2. Effect of $Fe_{71,1}Si_{18,6}B_{6,3}Nb_3Cu_1$ alloy on the hardness of PEEK (HRK scale) and UHMWPE (HRR scale) (**values are averages of 10 measurements*)

As a result, both the penetration of abrasive particles and the intensity of surface damage decrease. On the other hand, the uniform distribution of the nanofiller throughout the composite volume ensures a more even distribution of relaxation stresses arising in the friction zone and, consequently, reduces the likelihood of surface failure of the material. Confirmation of these processes is the reduction in the surface roughness parameter by 2,9 times for PEEK and 2 times for UHMWPE (Fig. 3) [7, 12].

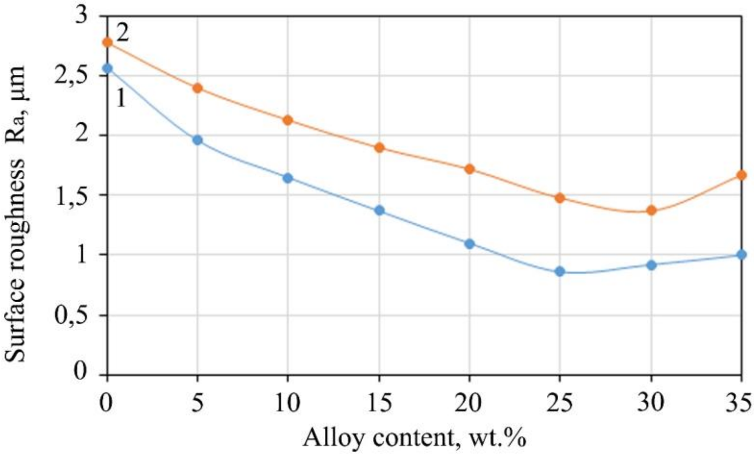

Fig. 3. Effect of $Fe_{71,1}Si_{18,6}B_{6,3}Nb_3Cu_1$ alloy on the surface roughness (R_a, µm) of PEEK and UHMWPE (**values represent averages of 10 measurements*)

Additional evidence is provided by the analysis of friction surface morphology. As shown in Fig. 4 a, b, multiple deformation defects (microcracks) are observed on the friction surface of the unfilled polymers, indicating their reduced resistance to the action of abrasive particles. In contrast, MPCMs exhibit significantly less damage to the surface layer (Fig. 4 c, d), indicating improved wear resistance to abrasive wear. The mechanism of improved wear resistance of the developed MPCMs filled with dispersed particles, compared to the initial polymer matrix, can be explained by the formation of external surface layers (ESLs) at the «polymer–nanoparticle» (polymer–NP) interface, which are characterized by enhanced functional properties. As a result, the cohesive strength of the MPCMs increases, improving their resistance to failure during friction. The introduction of dispersed particles of the nanocrystalline magnetic alloy $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ promotes the formation of thermodynamically non-equilibrium structures with ESLs, characterized by a higher degree of crosslinking, i.e., stronger intermolecular interactions between the polymer matrix and nanoparticles compared to neat polymers (PEEK and UHMWPE) [13]. This ensures improved interfacial bonding strength and stabilization of the MPCM structure under external loading.

It should be noted that the highest resistance to the action of rigidly fixed abrasive particles is exhibited by MPCMs containing 25 wt.% of the $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ alloy for PEEK and 30 wt.% for UHMWPE. A further increase in the NP content leads to a decrease in this property. This behaviour is typical of MPCMs filled with dispersed nanoparticles. Due to intermolecular interactions, these nanoparticles tend to interact with each other and form agglomerates, which hinders their uniform distribution within the polymer matrix and leads to the formation of local stress concentrations that act as sites for microcrack initiation. As a result, the porosity of the metal–polymer composite increases, while its strength and resistance to fracture decrease [3].

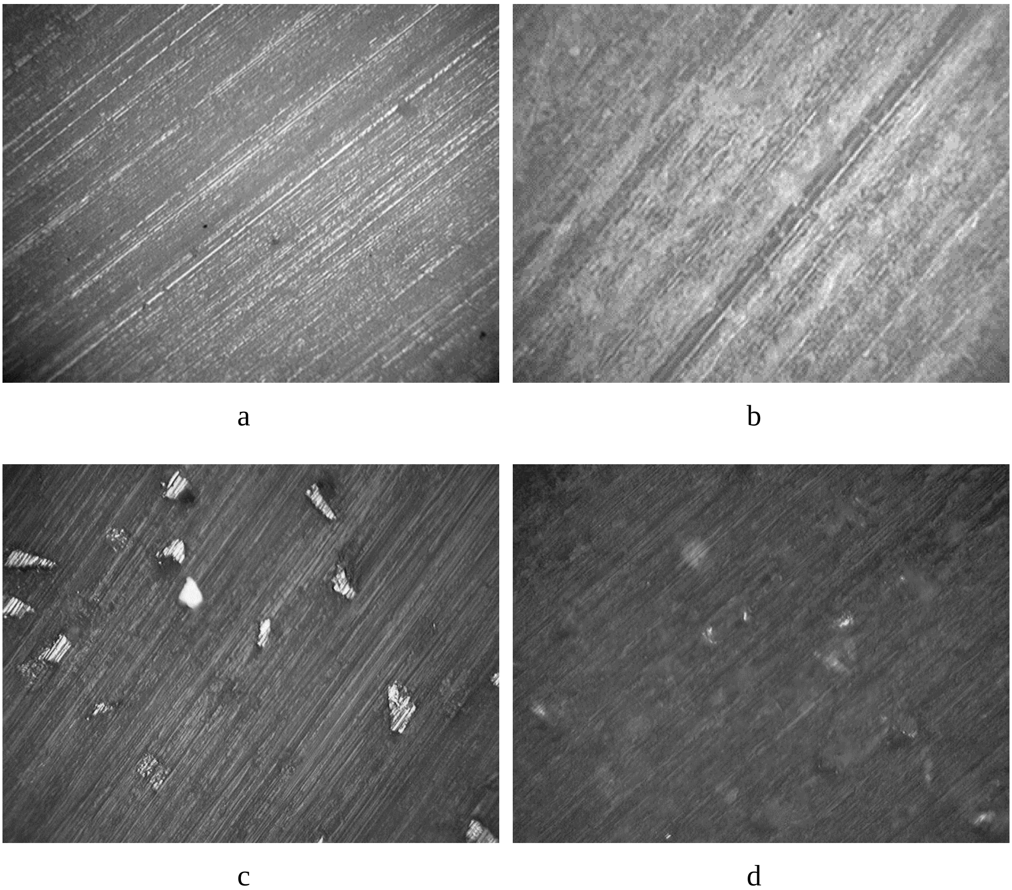

Fig. 4. Friction surfaces of PEEK (a) and UHMWPE (b); and composites containing 25 wt.% $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ based on PEEK (c) and UHMWPE (d)

Conclusion. It was found that the introduction of the nanocrystalline magnetic alloy $Fe_{71,1}Si_{18,6}B_{6,3}Nb_3Cu_1$ in the range of 5–30 wt.% results in a reduction in the abrasive wear index of PEEK and UHMWPE by 3 and 2,5 times, respectively. The optimal nanoparticle content is 25 wt.% for the first polymer and 30 wt.% for the second. The improvement in wear resistance is attributed to the high microhardness of the nanoparticles, which suppress microcutting and microplastic deformation, as well as the uniform distribution of the alloy within the PEEK and UHMWPE matrices, which reduces stress concentrations in the friction zone. This is supported by the decrease in the surface roughness parameter for both polymers. The developed MPCMs can be used for the manufacture of working components and auxiliary units of modern equipment operating under abrasive conditions.

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Received: May 07, 2026
Accepted: May 15, 2026
Published: May 31, 2026

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ВПЛИВ НАНОКРИСТАЛІЧНОГО СПЛАВУ $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ НА ПОКАЗНИК АБРАЗИВНОГО СТИРАННЯ ПОЛІЕФІРЕФІРКЕТОНУ ТА НАДВИСОКОМОЛЕКУЛЯРНОГО ПОЛІЕТИЛЕНУ

У роботі досліджено вплив вмісту нанокристалічного магнітного сплаву (ат.%) складу $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ (класу Finemet) на показник абразивного стирання поліефірефіркетону та надвисокомолекулярного поліетилену. Випробування проводили в умовах дії жорскозакріплених часток абразиву з використанням машини HECKERT, додатково визначали твердість і параметри шорсткості поверхні. Встановлено, що введення даного сплаву у кількості 5–35 мас.% призводить до зростання зносостійкості поліефірефіркетону у 2,9 рази та надвисокомолекулярного поліетилену у 2 рази. Підвищення зносостійкості досліджених металополімерних композиційних матеріалів можна пояснити тим, що дрібні (40 – 100 мкм) тверді частки сплаву $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$ (мікротвердість близько 15 000 МПа) перешкоджають розвитку процесів мікрорізання та мікропластичної деформації, зменшуючи глибину борозен проорювання, що підтверджується зменшенням параметра шорсткості поверхні поліефірефіркетону у 2,9 рази та надвисокомолекулярного поліетилену у 2,5 рази. Збільшення наповнювача до 30 мас.% для поліефірефіркетону та до 35 мас.% для надвисокомолекулярного поліетилену призводить до його агломерації, зростання пористості та зниження триботехнічних характеристик матеріалу. Розроблені металополімерні композиційні матеріали можуть бути рекомендовані для виготовлення робочих органів та допоміжних вузлів обладнання сучасної техніки, що працюють в агресивних умовах, зокрема під впливом абразивного середовища.

Ключові слова: поліефірефіркетон, надвисокомолекулярний поліетилен, показник абразивного стирання, нанокристалічний магнітний сплав $Fe_{71,1}Nb_3Cu_1Si_{18,6}B_{6,3}$

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