ISSN 1027-5495. Functional Materials, 30, No.3 (2023), p. 403-406.
doi:https://doi.org/10.15407/fm30.03.403

The dependence of the abrasive wear resistance of ultra-high-molecular-weight polyethylene on the content of mineral fillers with needle-like structure

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Received January 25, 2023

The paper studies the influence of the percentage of basalt fiber and wollastonite on the abrasion resistance index of ultra-high-molecular-weight polyethylene by hard-fixed abrasive particles. Studies have shown that adding basalt fiber (10–50 mass.%) or wollastonite (10–50 mass.%) to ultra-high-molecular-weight polyethylene reduces abrasive wear index by 35 %. The improvement of this indicator occurs due to mechanical destruction of the surface. It is confirmed by the study of the morphology of the friction surfaces (roughness decreases 1.5 times).
Keywords: ultra-high-molecular-weight polyethylene, basalt fiber, wollastonite, abrasive wear index, abrasive particles.

Залежність абразивної зносостійкості надвисокомолекулярного поліетилену від вмісту мінеральних наповнювачів із голкоподібною структурою
У роботі досліджено вплив відсоткового вмісту базальтового волокна та воластоніту на показник абразивного стирання надвисокомолекулярного поліетилену по жорстко-закріпленим абразивним часткам. Дослідження показали, що введення до надвисокомолекулярного поліетилену базальтового волокна (10–50 мас.%) чи воластоніту (10–50 мас.%) зменшує показник абразивного стирання на 35 %. Покращення даного показника обумовлено високою жорсткістю й міцністю наповнювачів, через що композити чинять більший опір до механічного руйнування поверхонь, що і підтверджує дослідження морфології поверхонь тертя (шорсткість зменшується у 1,5 р.).

1. Introduction

Nowadays, Ukrainian and world agricultural, metallurgical, and mining industries are abandoning the use of traditional alloys, highly alloyed and "heavy" metals in favor of ultra-high-molecular-weight polyethylene (UHMWPE). Thus, according to the forecasts of ResearchInChina [1], the use of UHMWPE will increase to 650 thousand tons per year in 2025, which is 55% more compared to 2021. This is due to the fact that high indicators of functional properties [2] allow the use of UHMWPE in the manufacture of various parts of protective elements (bodies of quarry dump trucks and wagons, buckets of bulldozers, seals, pressure bars, valves, pulleys, etc.) and tribological units (liners, gearwheels, gears, supporting rollers, cable blocks, etc.) that are subjected to wear and tear and work under the influence of shock loads and aggressive environments [3, 4]. It is known [5, 6] that the replacement of serial metal brake pads and gears with products made of UHMWPE on many self-propelled combines and harvesting machines used in the harvesting of grain and leguminous crops allows reducing the metal capacity by 23 thousand tons and increases the service life by 3 times. Various fillers are introduced into UHMWPE to improve its technical properties [7–10]: nanostructured vermiculite, carbon nanotubes, graphene nanoplates, mechanically activated cobalt and copper spinel, etc. The use of these fillers makes it possible to increase the wear resistance of UHMWPE 4–6 times, and increase strength and elasticity by 25 % and 35 %, respectively.

The aim of the work is to study of the influence of the filler (basalt fiber and wollastonite) on the tribotechnical properties of polymer composite materials (PCMs) based on ultra-high-molecular-weight polyethylene.

2. Experimental

UHMWPE was chosen as a polymer matrix. The technical properties of it are shown in Table 1.

Table 1. Properties of ultra-high-molecular-weight polyethylene

Indicator	Value
Density, g/sm^3	0.93–0.96
Viscosity, Mi/g	2650
Strength, MPa	35
Elongation at break, %	≥300
Maximum operating temperature, K	353
Water absorption, %	<0.01
Volatile matter, %	<0.1

The following materials were chosen as fillers for UHMWPE:

— discrete basalt fiber (BF) made of widespread rock, that is basalt. The use of BF as a filler makes it possible to obtain a composite with high corrosion and chemical resistance, and excellent mechanical and tribotechnical properties [11];

— wollastonite is a natural compound of calcium silicate ($CaSiO_3$) with a needle-like structure. PCMs containing wollastonite as a filler are characterized by high resistance to deformation and wear, strength in bending and stretching, and water and weather resistance [12].

Both fillers have a needle-like structure, that is, the ratio of diameter to length is more than 1:20, but the length does not exceed 150–200 μm.

PCMs based on UHMWPE containing 10–50 mass% of basalt fiber and wollastonite were prepared by dry mixing in an apparatus with a rotating electromagnetic field (0.12 T) using ferromagnetic particles, which were subsequently removed from the resulting mixture by magnetic separation. Prepregs were prepared at room temperature and a load of 5 MPa. The resulting prepregs were loaded into a mold heated to 313 K, then heated up to T_1 = 363 K and held at this temperature for 3 minutes without load, then heated up to T_2 = 433 K and kept at this temperature for 10 minutes under constant load (10 MPa). Then, the samples were cooled under constant load to a temperature of 313 K and removed from the mold.

The abrasion resistance index of UHMWPE and PCMs based on it was studied using rigidly fixed abrasive particles (dispersion of 100 μm) on a HECKERT testing machine. Before the start of the experiment, each sample underwent a preliminary running-in in the operating mode until full contact with the abrasive skin was reached. The load on the sample during the experiment was 10 N; the friction path was 40 m.

The value of the abrasive wear index (V_i, mm^3/m) was determined by the formula:

$$V_i = \frac{\Delta G \cdot 1000}{\rho_e \cdot L},$$

where ΔG is the amount of mass wear, g;

ρ_e is the experimental density of the material that wears, g/cm^3?;

L is a friction path (40 m), in one cycle.

The experimental density of PCMs was calculated by the ratio of the mass of the sample in air (m_1) to the difference in the mass of the sample in air and in isopropyl alcohol (m_2):

$$\rho_e = \frac{m_1}{(m_1 - m_2)} \cdot \rho_c,$$

where m_1 is the mass of the test sample in air, g;

m_2 is the mass of the experimental sample in alcohol, g;

ρ_c is the density of isopropyl alcohol (0.786 g/cm^3).

The morphology of the friction surfaces of UHMWPE and PCMs was studied using a BIOLAM-M microscope. The roughness of friction surfaces of UHMWPE and composites based on it was measured using a 170621 probe profilometer on the R_a (μm) scale.

3. Results and discussion

The analysis of the results of tribotechnical properties (see Table 2) of PCMs shows that the use of BF and wollastonite is a promising way to reduce the abrasive wear index of UHMWPE by 35 %. This indicator is improved due to the high stiffness and strength of the fillers; as a result, PCMs

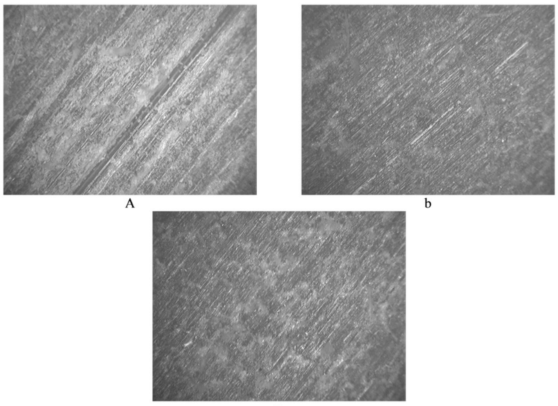

Fig. 1. Friction surfaces (×200) of ultra-high-molecular-weight polyethylene (a) and composites based on it containing 20 mass% of basalt fiber (b) and wollastonite (c).

are more resistant to mechanical destruction of surfaces [14].

It can be concluded from the obtained microstructures (Fig. 1) of UHMWPE and composites based on it that the introduction of BF and wollastonite strengthens the polymer matrix, and, as a result, there is an increase in the resistance of the composite surfaces to mechanical destruction that develops during friction. This is confirmed by the decrease in PCMs roughness 1.5 times (see Table 2).

It is interesting to note that with an increase in the number of test cycles (see Fig. 2, Fig. 3), the abrasive wear index of both UHMWPE and composites based on it decreases. This is due to the fact that finely dispersed wear products fill the microcavities of the abrasive skin, as a result of which there is a "salting" of the surface.

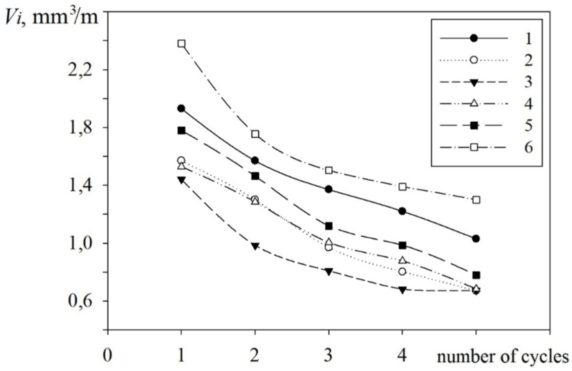

Fig. 2. Dependences of abrasive wear index (V_i, mm^3/m) on the number of research cycles for ultra-high-molecular-weight polyethylene (*1*) and composites containing 10 (*2*), 20 (*3*), 30 (*4*), 40 (*5*), 50 (*6*) mass% basalt fiber.

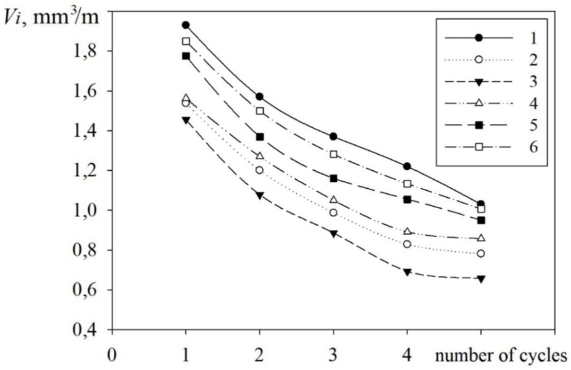

Fig. 3. Dependences of the abrasive wear index (V_i, mm^3/m) on the number of research cycles for ultra-high-molecular-weight polyethylene (*1*) and composites containing 10 (*2*), 20 (*3*), 30 (*4*), 40 (*5*), 50 (*6*) mass% wollastonite.

It should be noted that the greatest increase in the wear resistance of UHMWPE is observed when the content of BF or wollastonite is 10–20 mass%. A further increase in the filler content to 50 mass% in the polymer matrix leads to a deterioration of this indicator. The obtained results can be explained as follows. As the content of the filler increases, it becomes more difficult to achieve its uniform distribution, and as a result, its clusters are formed (see Fig. 4). These clusters are not permeated by

Table 2. Operational properties of UHMWPE and composites based on it

Filler content, mass%	Abrasive wear index *, V_i, mm^3/m		Roughness* R_a, μm	
	basalt fiber	wollastonite	basalt fiber	wollastonite
0	1.36	2.57		
10	1.05	1.06	2.07	2.13
20	0.92	0.97	1.71	1.99
30	1.17	1.12	2.46	2.29
40	1.22	1.13	2.67	2.41
50	1.61	1.25	2.73	2.53

[*] average value

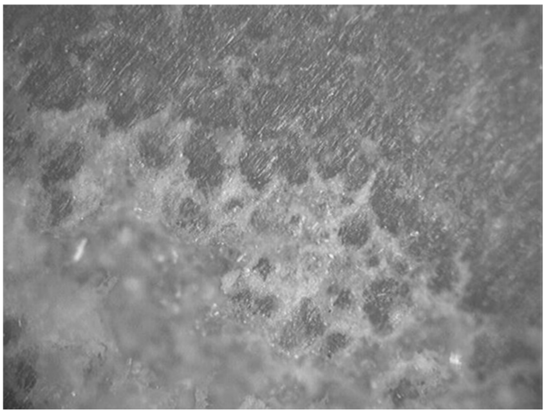

Fig. 4. Friction surface (×200) of an ultra-high-molecular-weight polyethylene composite containing 50 mass% of wollastonite.

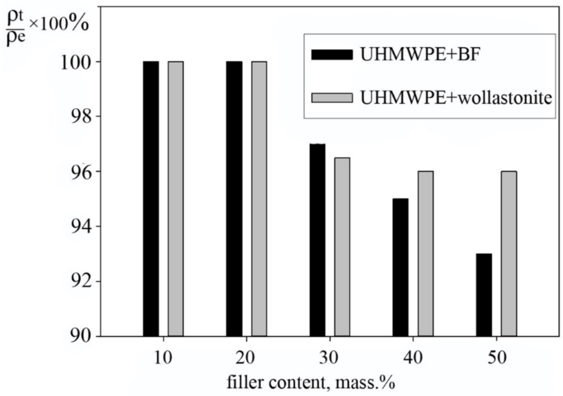

Fig. 5. The ratio of theoretical (ρ_t) and experimental (ρ_e) density.

the melt of the polymer matrix; there are voids inside them [15].

On the other hand, this can be explained by the fact that UHMWPE enters a viscoelastic state while melting [2–3], that is, the melt is characterized by high viscosity and low mobility of macromolecules; as a result, insufficient impregnation of the filler with polymer occurs, and, consequently, the number of pores and voids increases. Another confirmation of the increase in the number of pores in the PCMs volume is the ratio of their theoretical density to the experimental one. As can be seen from Fig. 5, this ratio is less than 100 % for composites containing 30–50 mass%, which indicates the presence of defects.

4. Conclusions

Analysis of the obtained results showed that the use of discrete basalt fiber and wollastonite as fillers for UHMWPE is a promising way to improve its tribotechnical properties: the abrasive wear index and roughness reduced by 1.45 and 1.5 times, respectively. It was established that the effective content of the filler for UHMWPE is 20 mass% of basalt fiber or wollastonite.

The structure of composites with acicular wollastonite (30–50 %) is more ordered, compared to basalt fiber; this conclusion is confirmed by the fact that the calculated and experimental densities of composites with BP have a more significant difference. This is probably due to the fact that wollastonite ($CaSiO_3$) has a more homogeneous chemical composition, in contrast to the multicomponent (SiO_2, Al_2O_3, Fe_2O_3, CaO, TiO_2, etc.) composition of BF; as a result, the interaction of wollastonite and UHMWPE at the molecular level occurs with a smaller number of pores, which is also confirmed by the results of the change in the abrasive wear index depending on the amount of filler.

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