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Influence of Component–Mixing Methods on the Properties and Structure of UHMWPE-Based Composites

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Abstract—The article studies the how the component-mixing method, based on application of joint mechanochemical processing of composite components and ultrasonic action, influences the mechanical and tribological characteristics of UHMWPE–carbon-fiber polymer composite materials. It has been established that joint activation of the components and ultrasonic treatment leads to a 10–15% increase in strength and elastic modulus while retaining the elasticity of composites at the level of the initial polymer matrix. A decrease in the friction coefficient by 30% and mass wear rate by 5.5 times compared to 1.6 for the initial matrix were recorded.

Keywords: ultra-high molecular weight polyethylene, carbon fiber, ultrasonic treatment, joint activation, mass wear rate, friction coefficient, friction surface

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INTRODUCTION

One modern task of materials science is to use novel technologies and designs adapted to the natural and climatic conditions of the Arctic. Therefore, to significantly increase the reliability and durability of equipment, it is necessary to develop and accelerate the implementation of new materials with significantly improved technical characteristics.

The development of new tribotechnical materials based on frost-tolerant polymer composites with a significantly improved set of operational properties can significantly increase the low-temperature operability of equipment and reduce repair costs and losses from downtime [1–3].

Among the polymer matrices used to manufacture friction-unit parts in cryogenic technology, as well as machines and mechanisms designed for use in cold climates, ultrahigh molecular weight polyethylene (UHMWPE) is especially interesting. UHMWPE possesses extremely high impact strength, wear resistance, frost tolerance, and hydrophobicity [4–6]. Global production of UHMWPE and its applications are constantly expanding. UHMWPE materials are also recommended for protection (lining) of parts and structural elements exposed to abrasive and hydroabrasive effects.

It is well known that reinforced polymers are promising for vital structures and the friction units of machines and mechanisms. Despite the large number of modern reinforcing fillers, carbon fiber (CF) is the most widely used, since it has unique chemical, electrical, and mechanical properties [7, 8]

Objective—To study how various PCM-component-mixing methods affect the mechanical and tribological performance characteristics of UHMWPE–CF.

MATERIALS AND METHODS

The study objects are GUR 4150 UHMWPE manufactured by Ticona. The average particle size is ≈120–150 μm, and the molecular weight is ≈9.2 million. The filler is Belum, LO-1-12N/40 CF, the surface has a layer of organofluorine compounds deposited by plasma-chemical treatment (OJSC SvetlogorskKhimvolokono, Belarus). Fibers have a diameter of 7.7–10.8 μm and length up to 300 μm (up to 90%).

A powder composition of UHMWPE and discrete CF was obtained by dry mixing weighed components in a high-speed paddle mixer with a rotor speed of 300 rpm for 2–4 min. Then. the powder compositions were additionally subjected to treatment in an Laborette 17 ultrasonic water-filled bath, through a capacitance transmitting ultrasonic vibrations for 20 min; the ultrasound frequency was 35 kHz. Thus, the powder compositions were subjected to treatment in dry form. The components were coactivated out in a Pulverisette 5 planetary mill for 2 min. Next, samples for testing were obtained by hot pressing.

Table 1. PCM mechanical characteristics depending on production technology

Test material	ε_p, %	σ_p, MPa	E_m, MPa	σ_{com} at 25% deformation, MPa
UHMWPE (GUR-4150)	280 ± 10	36.0 ± 1.5	810 ± 40	34.6 ± 1.5
UHMWPE + 5 wt % Belum, pm	290 ± 14	36.0 ± 1.5	863 ± 43	39.2 ± 1.9
UHMWPE + 5 wt % Belum, US	283 ± 14	39.3 ± 1.9	932 ± 46	40.1 ± 2.0
UHMWPE + 5 wt % Belum, coact	274 ± 13	41.2 ± 2.0	920 ± 46	42.1 ± 2.1

ε_p, elongation at break; σ_p, tensile strength; E, elastic modulus; σ_{com}, compressive strength.

The mechanical characteristics (elongation at break, tensile strength, elastic modulus) of the samples (type 5 blades) were studied on a UTS-20 K tensile testing machine at a sliding-gripper rate of 50 mm/min. Five samples were investigated in parallel; the error of the results was 0.9% (GOST 11262). The gripper speed when determining compressive strength was 2 mm/min. The mass wear rate and friction coefficient were determined on an II-5018 friction machine according to the finger–disk scheme; the counterbody was a disk made of 45 steel with a diameter of 75 mm, a hardness of 45–50 HRC, and a roughness of R_a = 0.06–0.07 μm. The test sample was a column with a diameter of 10 mm and height of 15 mm; three parallel tests were carried out; the error in measuring the wear rate was 5%. The friction mode was a load of 200 N and a linear sliding speed of 0.5 m/s. The test time was 3 h. Structural studies were performed on a JEOL JSM-6480LV scanning electron microscope. Hardness was determined with a TEMP-2 electronic hardness tester.

RESULTS AND DISCUSSION

CF was introduced into the polymer matrix in an amount from 1 to 10 wt % It was revealed that the composite with a hydrocarbon content of 5 wt % possesses the optimal set of properties [9]. Therefore, the influence of various technological methods for producing composites was subsequently compared on composites with a hydrocarbon content of 5 wt % (Table 1).

It has been established that mechanical coactivation of components and ultrasonic treatment of the powder composition with Belum CF leads to an increase in the strength indices and elastic modulus by 10–15% compared with the initial polymer and composite obtained by paddle mixing (standard technology) while retaining elasticity of the PCM at the level of the initial polymer (Table 1).

Figure 1 clearly shows a decrease in the mass wear rate by 4.5–5.5 times for ultrasound and mechanical coactivation of the composite components compared to the initial UHMWPE. An increase in wear resistance by 1.3 times is established in comparison with the properties of the composite obtained by the standard method. The friction coefficient decreases by up to 1.5 times compared with the initial UHMWPE. Apparently, the use of high-energy techniques for processing components contributes to an increase in adhesive interaction in the polymer–filler system, which leads to an increase in hardness and elastic modulus. As is well known, increasing the stiffness of composites reduces the deformation component of friction, lowering the friction and wear coefficients [10].

A decrease in the PCM wear rate can also indicate the formation of a secondary structure on friction surfaces oriented in the sliding direction [11]. The significant transformation of the surface layers of composites under frictional loading and the formation of secondary structures have been confirmed by micrographs of the friction surfaces of the initial UHMWPE and PCM based on it (Fig. 2).

Figure 2c shows a ×5000 magnification of the area in Fig. 2b, which clearly shows that the CF is subjected to abrasion. This gives grounds to suppose that when PCM rubs against a steel counterbody, the frictional contact areas are at the locations of CFs, which, being stronger and harder than the polymer matrix, impede the tribological destructive processes of the material, thereby reducing the PCM wear rate.

As well, the formation of secondary structures on the friction surface is confirmed by the increase in

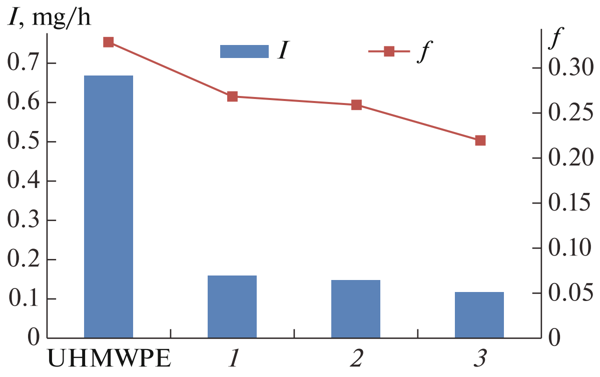

Fig. 1. Dependence of the mass wear rate and the friction coefficient on the method of obtaining PCM: (*1*) UHMWPE + 5 wt % Belum (simple mixing); (*2*) UHMWPE + 5 wt % Belum (US); (*3*) UHMWPE + 5 wt % Belum (coactivation).

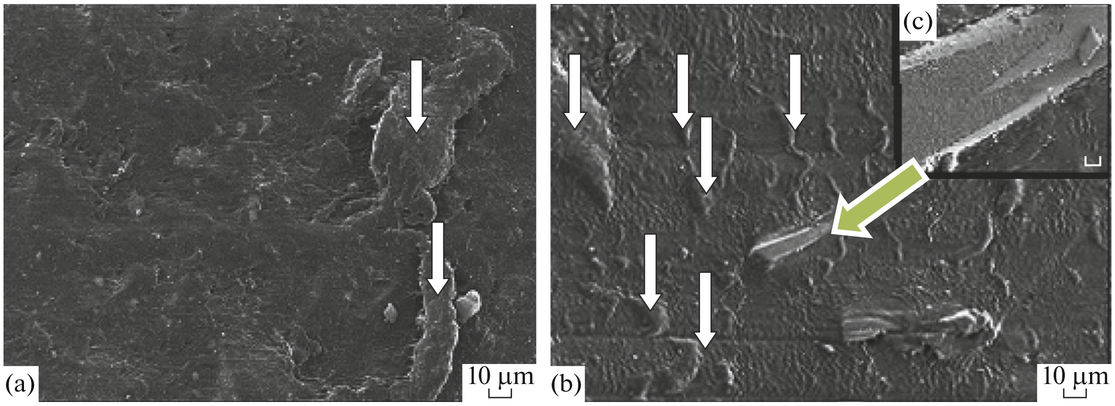

Fig. 2. Micrographs of friction surface: initial UHMWPE (×500); UHMWPE + 5 wt % Belum (US) (×500); (c) magnified image of (b) (×5000). Arrows indicate secondary structures.

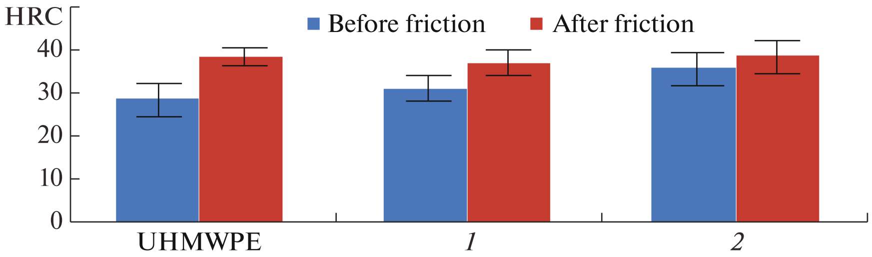

Fig. 3. Dependence of hardness of friction surface on method of obtaining PCM: (*1*) UHMWPE + 5 wt % Belum (US); (*2*) UHMWPE + 5 wt % Belum (coact).

PCM hardness (Fig. 3) after friction as a result of the surface effect of "healing" of microdefects on the PCM surface due to local melting of wear products on the friction surface [12–14].

CONCLUSIONS

Technological methods have been developed for combining a polymer with carbon fibers based on joint mechanochemical processing of composite components and ultrasonic treatment to obtain durable and wear-resistant UHMWPE-based composites.

It is shown that coactivation methods lead to a decrease in the mass wear rate up to 5.5 times compared with the initial polymer, along with a decrease in the friction coefficient. The mass wear rate is reduced by 1.3 times in comparison to the properties of the composite obtained by standard mixing. An increase in the strength of composites is observed in comparison with composites obtained by the standard technology.

Tribo-oriented PCMs with increased strength, wear resistance, and low friction coefficient have been developed.

NOTATION

UHMWPE	ultra-high molecular weight polyethylene
PCM	polymer composite material
CF	carbon fiber
ε_p	elongation at break
I	mass wear rate
σ_p	tensile strength
f	friction coefficient
σ_{com}	compressive strength at 25% deformation
pm	paddle mixer
US	ultrasound
coact	coactivation

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