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Comparison of mechanical and tribotechnical properties of UHMWPE reinforced with basalt fibers and particles

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Abstract. Mechanical and tribotechnical properties of UHMWPE composites reinforced with basalt fibers and particles under dry sliding friction and abrasion were investigated. It is shown that adding of the basalt particles provides higher wear resistance under the dry sliding friction while at abrasion filling by the basalt fibers is more efficient since the wear resistance of the reinforced UHMWPE composites is by 3.7 times higher in contrast with the neat polymer. Wear mechanisms of the polymeric UHMWPE composites under various types of wear are discussed.

1. Introduction

Composites based on ultra-high molecular weight polyethylene (UHMWPE) are widely used in various industries. The application of composite materials with the UHMWPE matrix makes it possible to multiply increase the wear resistance of “metal-polymer” friction units. Recently, micro- and nanocomposites based on UHMWPE are actively developed [1-4].

At design of composite materials based on UHMWPE matrix their preferential operation conditions are to be taken into account: i) abrasion wear (e.g. liners of transporters or carriages); ii) dry sliding friction (gear wheels or gear transmission); iii) friction under boundary lubrication (polymer components of artificial joints).

During in-field exploitation the products made of UHMWPE matrix may experience all three above-mentioned types of wear. In this concern it is reasonable to use the fillers that can provide improvement of wear resistance to various types of wear, as well as to provide higher strength, lower friction coefficient, etc. In doing so, various particulate and fibrous materials are used to fill the polymers [5].

Note that composites filled with the basalt fibers are actively developed. This is related to their high mechanical properties, low cost and ecological compatibility, since the basalt is a natural mineral, whose main chemical components are SiO_2, Al_2O_3, CaO, MgO, Fe_2O_3 [6-9]. The melting temperature of the basalt makes 1500-1700 °C.

Regardless the fact that results on studying UHMWPE composite materials filled with the basalt fibers are reported in the literature the topic on the influence of filler size and shape are of particular importance in the sense structure formation as well as mechanical and tribotechnical properties.

This paper deals with the comparative analysis of basalt fibers and particles reinforced UHMWPE composites. The issues of structure formation as well as mechanical and tribotechnical properties under dry sliding friction and abrasive wear are studied.

2. Experimental

Ultra-high molecular weight polyethylene (UHMWPE) produced by Ticona (GUR-2122) with molecular weight 4.0 million and characteristic particle size of 5-15 μm, basalt particles with characteristic diameter of 7÷15 μm, basalt fiber with length of 260 μm and diameter of ~13 μm (aspect ratio 20:1) were used in the study. Specimens of polymeric composites were fabricated by hot isostatic pressing under specific pressure of 10 MPa and sintering temperature of 200 ºC with subsequent cooling rate of 1.5ºC/min.

Mechanical properties were determined with the help of the electromechanical testing machine Instron 5582 under uniaxial tension. Specimens were dog-bone shaped. The number of specimens of the each type was equal to 4. Friction coefficient for the specimens was measured by the "ball-on-disk" scheme with the help of tribometer “Tribotechnique” (France). Tests were carried out at the indenter sliding speed of 0.3 m/s (according to ASTM G99-95a and DIN 50324). The diameter of the indenter made of high strength steel was equal to 6 mm. The load makes 5 N.

Wear resistance under dry sliding friction was determined by "block-on-ring" scheme under loading of 68.8 N and disk rotation speed of 100 rev/min (according to ASTM G99). The SMT-1 wear testing machine was employed (sliding velocity – 0.32 m/s). Wear track surfaces of the specimens were examined by the optical profilometer New View 6200 (Zygo).

Abrasion testing was conducted with the help of MI-2 testing machine intended for the rubber abrasion (finger-on-disk). Abrasive wear resistance was evaluated under the load of 0.15 MPa. Sliding velocity of the steel disk regarding to the pair of polymeric specimens was equal to 17.0 m/min. Sand paper with fixed abrasive particles grade 240 P (grain size of 58.5 μm) was used. Volumetric abrasion was measured by weight loss for every 5 minutes. The test procedure meets the requirements of ASTM G99 and DIN 50324. Tribotechnical characteristics were evaluated by averaging the measuring data over four specimens of each type.

Permolecular structure investigations were carried out by the scanning electron microscope LEO EVO 50 at the accelerating voltage of 20 kV. Rupture surfaces were obtained by mechanical fracturing of notched specimens after preliminary exposure in liquid nitrogen.

3. Results and discussion

Tables 1 and 2 show the tribotechnical and mechanical properties of UHMWPE composites filled with the basalt fibers and particles. It is seen that with increasing basalt fillers weight fraction the density of the UHMWPE based polymeric material increases. If this takes place the Shore D hardness varies slightly as compared to neat UHMWPE. Tensile strength is reduced but slightly when adding more than 5 wt. % of the basalt fibers or particles. The value of elongation at failure for the composites “UHMWPE + n wt. % basalt filler” is also reduced. The friction coefficient *f* is increases from 0.120 to 0.152 when adding 20 wt. % of basalt fibers and up to 0.150 when adding 20 wt. %. of the basalt particles.

Table 1. Mechanical and tribotechnical characteristics of UHMWPE and composites “UHMWPE + n wt.% of basalt fibers”

Basalt fiber content, wt.%	Density ρ, g/cm^3	Shore hardness, *D*	Tensile strength σ_U, MPa	Elongation ε ,%	Friction coefficient ,*f*
0	0.934	57.7±0.6	32.3±1.7	485±24	0.120
5	0.960	58.75±0.7	33.7±1.9	415±27	0.134
10	0.990	55.34±0.7	31.5±1.9	409±59	0.126
20	1.054	60.1±0.6	29.1±1.9	345±55	0.152

Table 2. Mechanical and tribotechnical characteristics of UHMWPE and composites “UHMWPE + n wt.% of basalt particles”

Basalt particles content, wt.%	Density ρ, g/cm^3	Shore hardness, *D*	Tensile strength	Elongation ε ,%	Friction coefficient ,*f*

			σ_U , MPa		
0	0.934	57.7±0.6	32.3±1.7	485±24	0.120
5	0.962	55.6±0.9	32.5±2.2	439±40	0.112
10	0.991	56.4±0.8	30±1.7	410±36	0.136
20	1.063	56.9±0.9	31.5±2.8	401±26	0.150

In doing so, the strength properties of UHMWPE composites filled with the basalt fibers and particles are not substantially changed with increasing content of the fillers.

Tribotechnical properties of the UHMWPE composites filled with the basalt depend on the filler shape (fibers or particles). The diagrams of wear intensity of the wear track surface as well as its roughness for the UHMWPE reinforced with the basalt fibers and particles under dry sliding friction are shown at Figure 1 and 2 correspondingly. It can be seen that the wear resistance of the composites "UHMWPE + n wt. % of basalt fiber" is increased when adding 5 wt. % of the filler while further it sharply decreases. Similar trend is characteristic for the wear track surface roughness as the function of the fiber weight fraction.

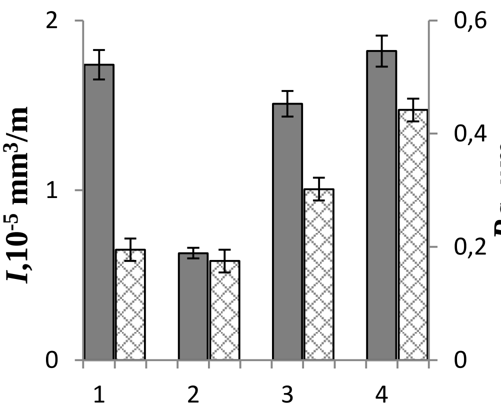

Figure 1. Wear rate (I) and surface roughness of the wear track (Ra) under dry sliding friction of UHMWPE composites filled with basalt fibers:(1) – UHMWPE, UHMWPE+ basalt fibers (2) – 5 wt. %, (3)– 10 wt. %, (4)– 20 wt. %

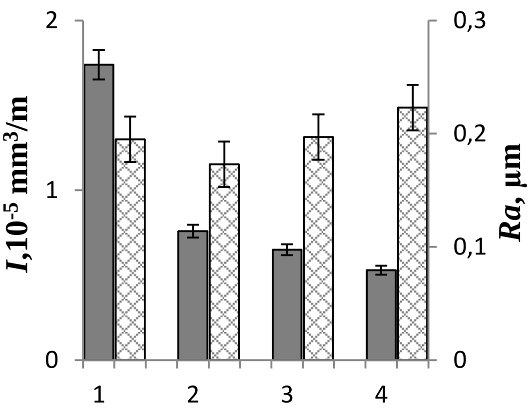

Figure 2. Wear rate (I) and wear track surface roughness (Ra) under dry sliding friction of UHMWPE composites filled with basalt particles: (1)– UHMWPE, UHMWPE+ basalt particles (2)– 5 wt. %, (3)– 10 wt. %, (4) – 20 wt. %

A quite different trend for the dependence of the wear rate versus the filler content is observed in the composites with basalt particles (Figure 2). It is seen that the wear resistance of the UHMWPE composites increases with enlarging particle weight fraction up to 20 wt. %. In doing so, the surface roughness of wear track surface in the composites is close to one in pure UHMWPE. Similar results were observed in our previous studies for UHMWPE composites filled with microparticles (aluminum oxide, aluminum oxyhydroxide, hydroxyapatite) [6].

The optical and SEM micrographs of the wear track surface morphology as well as permolecular structure of the composites with the basalt fibers and particles are shown in Figure 3 and Figure 4. It is seen that type and content of the filler affect them substantially. The obvious microscratches are formed on the friction surface. This pattern is made more manifested when the fiber content is enlarged. Most likely these scratches are resulted from destructive effects of the broken fibers that cut the surface of the softer polymeric matrix (Figure 3, c, d).

On the other hand, when adding the basalt particles into the UHMWPE matrix formation of spherulite permolecular structure is suppressed (Figure 3, c, d). Note that the basalt particles are uniformly

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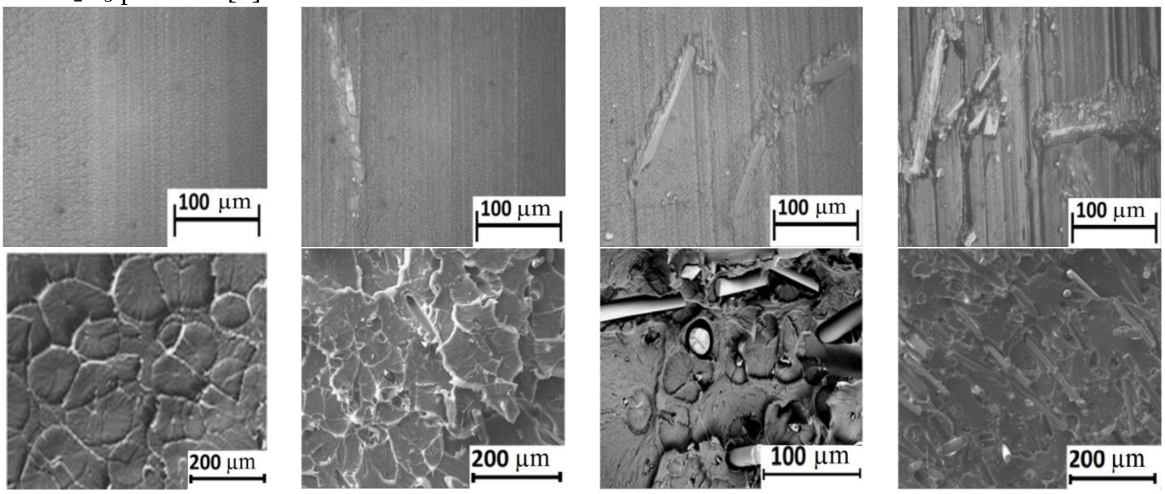
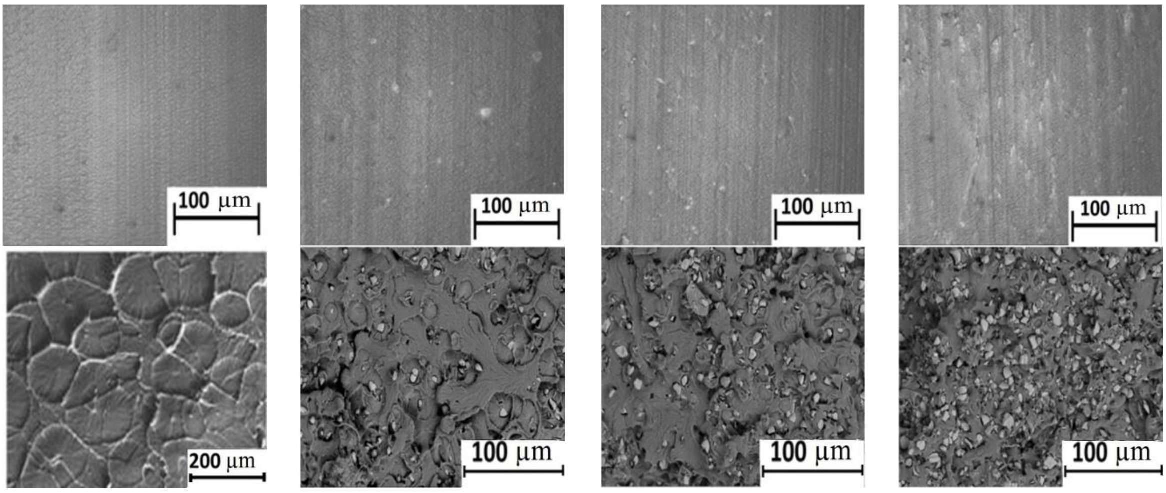
distributed in the matrix. In doing so under the dry sliding friction they act as oscillating "strings" providing a sufficiently smooth wear surface of the composite with high level of wear resistance (Figure 4). Similar results were obtained in our previous studies of the UHMWPE composites filled with Al_2O_3 particles [6].



a) b) c) d)

Figure 3. Optical and SEM micrographs of wear track surfaces under dry sliding friction and permolecular structure: UHMWPE (a), UHMWPE + 5 wt. % of the basalt fiber (b), UHMWPE + 10 wt. % of the basalt fiber (c), UHMWPE + 20 wt. % of the basalt fiber (d)



a) b) c) d)

Figure 4. Optical and SEM micrographs of wear track surfaces under dry sliding friction and permolecular structure: UHMWPE (a), UHMWPE + 5 wt. % of basalt particles (b), UHMWPE + 10 wt. % of basalt particles (c), UHMWPE + 20 wt. % of basalt particles (d)

At abrasive wear tests the role of the basalt fibers and particles in the formation of the tribotechnical properties of UHMWPE composites is reversed. Note, that in our previous studies it was shown that the size ratio of fixed abrasive particles and that of the filler plays a decisive role at abrasive wearing of polymeric composites [6,10].

The data on abrasive wear intensities of the UHMWPE composites filled with the basalt fibers and particles are shown at Figure 5 and 6. It is seen from figure 5 that increasing the basalt fiber content up to 10 wt. % results in increase of the abrasive wear resistance of the composites: at filling degree of 10 wt. % it rises by 2.8 times. With adding the basalt particles the opposite effect is evident: abrasive wear resistance is decreased: at filling degree of 10 and 20 wt. % it is nearly equal to that of the pure UHMWPE (Figure 6). Roughness of the wear track surfaces possesses the same trend.

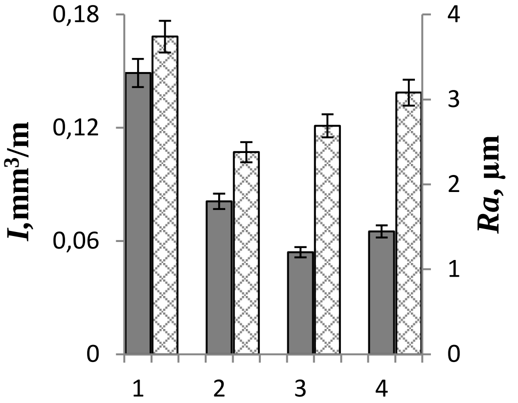


Figure 5. Wear rate (*I*) and surface roughness of wear track (*Ra*) under abrasive wear of UHMWPE composites with the basalt fibers: 1 – UHMWPE, UHMWPE + basalt fibers of 2) – 5 wt. %, 3) – 10 wt. %, 4) – 20 wt. %. P 240

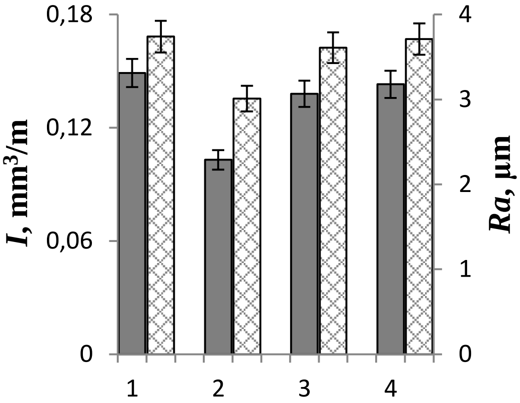


Figure 6. Wear rate (*I*) and surface roughness of wear track (*Ra*) under abrasive wear of UHMWPE composites with the basalt particles: 1 – UHMWPE, UHMWPE + basalt particles of 2) – 5 wt. %, 3) – 10 wt. %, 4) – 20 wt. %. P 240

Figure 7 shows the optical profilograms of the wear surface under abrasion of the composites with basalt fibers (a-d) and particles (e-h). Long basalt fibers resist the destructive action (cutting) of fixed abrasive particles (58.5 µm) and partly protect the matrix. At the same time the basalt particles has much smaller size (7 µm versus 58.5 µm). Therefore they are not able to protect the matrix from ploughing and cutting by less brittle abrasive particles of higher hardness.

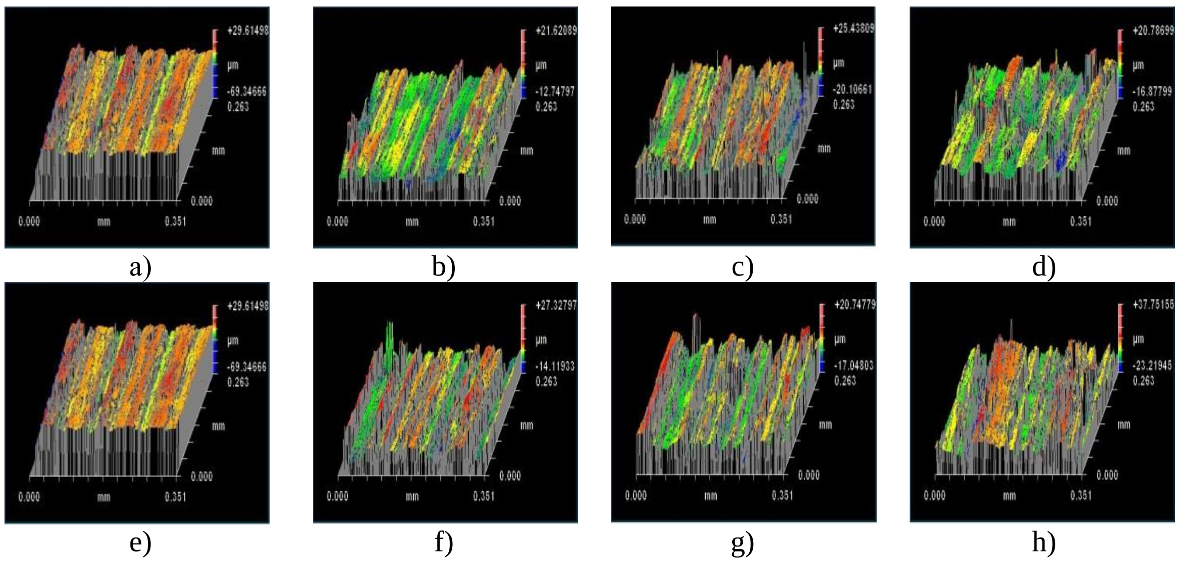


Figure 7. Optical profiles of wear surfaces: UHMWPE (a, e) and UHMWPE composites: + 5 wt. % of basalt fibers (b), + 10 wt. % of basalt fibers (c), + 20 wt. % of basalt fiber (d), + 5 wt. % of basalt particles (f), + 10 wt. % of basalt particles (g), + 20 wt. % of basalt particles (h). Abrasive wear. P 240

4. Conclusions

The mechanical properties (hardness, tensile strength, elongation) vary slightly at filling UHMWPE with the basalt fibers and particles (at their content up to 10 wt. %).

Formation of the spherulitic permolecular structure is suppressed when filling the UHMWPE matrix with basalt fibers and particles with weight fraction more than 5 wt. %.

The reinforcement of the UHMWPE-matrix by the basalt particles is effective under dry sliding friction: wear resistance of the composites increases 3-fold when 20 wt. % of the filler is added.

Adding basalt fibers into UHMWPE provides improvement of the abrasive wear resistance which is increased by 2.5 times when filler weight fraction is varied in the range of 10-20 wt. %.

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