Oil filled polymer composites based on ultrahigh-molecular-weight polyethylene

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Abstract. In recent years, a method of increasing the frictional properties of polymeric materials by introducing liquid lubricating oils into their composition has become widespread. The aim of this work is to create new wear-resistant polymer composite materials based on ultrahigh-molecular-weight polyethylene (UHMWPE) with liquid-phase filling. When UHMWPE is filled with lubricating oil, there is an increase in wear resistance by 4 times compared with the original UHMWPE.

1. Introduction
The use of polymer composites is one of the most effective ways to improve performance of equipment. Currently, there are many different industrial polymers which are used in different kind of parts of machinery and equipment. However, only a small number of polymers can be used as material for friction units. The reasons usually are poor wear resistance or high friction coefficient. Currently, methods of processing polymer nanocomposites based on UHMWPE with high frost resistance and wear resistance are being actively developed, which makes it possible to use materials based on it under the extreme conditions of the Arctic [1,2]. Despite high wear resistance UHMWPE cannot be exploited under high loads because of high friction coefficient and thus high temperature in friction zone [3]. In recent years, the method of increasing the antifriction properties of polymeric materials by introducing liquid-phase lubricants and lubricating oils into their composition has become widespread [4,5]. Earlier, in [6], it was found that after ultrasonic treatment the surface of UHMWPE particles is smoothed, the number and depth of surface pores and voids decreases significantly due to surface sintering caused by a significant increase in temperature and pressure under the influence of ultrasound. Thus, the purpose of this work is to create new wear-resistant polymer composite materials based on UHMWPE by encapsulating lubricating oil in UHMWPE particles.

2. Models and Methods
UHMWPE of Celanese GUR 4022 grade (China) was used as a polymer matrix. UHMWPE has the molecular mass of 5.0 × 10⁶, bulk density of 0.4 g/cm³, and mean particle diameter of 150–200 μm. Engine oil ENEOS Super Gasoline 5W30 (the Republic of Korea) and Drying oil Oxol (Russia) (GOST 190-78) were used as a liquid filler.

A weighed mass of 60 g of dried UHMWPE is mixed with 80 ml of liquid filler, and then treated in an IL 100-6/3 ultrasonic disperser in three different powers – 750 W, 1,125 W, 1,500 W.
After treatment of UHMWPE suspension with oil by ultrasonic waves, the mixture is separated, and UHMWPE is washed with an organic liquid. Washed UHMWPE is dried at t=100°C. UHMWPE and its composites are processed by hot pressing at specific moulding pressure of 10 MPa and temperature of 175°C, with prepressing to remove residue air at 2 MPa. Compressive strength at the established relative deformation equal to the values x = 2.5; 10; 25% is determined according to ASTM D 3410/D on cylindrical specimens with a diameter of 10 mm at a speed of compressing grippers of 1 mm / min. The hardness was determined by the method of ball indentation method (ISO 2039 / 1-87). The diameter of the steel ball indenter was 5 mm, the measurement accuracy of the indentation depth was ± 0.005 mm, the indentation time was ± 0.1 s, and the test load was 132 N. The sample was a flat sample with dimensions of 10 x 10 mm and a thickness of 4 mm.

Tribological characteristics of composites (friction coefficient, mass wear rate) were determined on a universal tribometer UMT-2 (CETR, USA) according to the pin-on-disc friction scheme based on GOST 11629-75 by sliding samples on the steel counterbody under a load of 150 N and sliding speed of 1 m / s. The IR spectra of PCM samples were recorded on a Varian FTIR 7000 spectrometer in the range of 500–4000 cm\(^{-1}\). Oxidation index was calculated in accordance with ISO 5834-4: 2005 as ration between area of peaks in the region 1660 – 1800 cm\(^{-1}\) and area of peak in the region 1370 cm\(^{-1}\).

### 3. Results and Discussion

The mechanical properties of nanocomposites were characterized by hardness and compressive strength. In Table 1, the compressive strength and hardness of the composites are shown depending on the power of the ultrasonic vibration on the suspension of the polymer in a liquid medium.

| Power of ultrasound, W | UHMWPE + engine oil | UHMWPE + drying oil |
|------------------------|----------------------|---------------------|
| σc, MPa\(^a\) | H, N/mm\(^2\)\(^b\) | σc, MPa\(^a\) | H, N/mm\(^2\)\(^b\) |
| 2.5% | 10% | 25% | 2.5% | 10% | 25% | 2.5% | 10% | 25% |
| 0 | 7.5 | 18.6 | 29.0 | 35.00 | 0 | 7.5 | 18.6 | 29.0 | 35.00 |
| 750 | 10.8 | 24.4 | 35.8 | 26.22 | 750 | 11.7 | 25.2 | 36.7 | 35.39 |
| 1,125 | 10.1 | 24.6 | 36.8 | 35.39 | 1,125 | 9.8 | 23.8 | 35.5 | 35.39 |
| 1,500 | 8.6 | 21.9 | 32.5 | 28.32 | 1,500 | 11.4 | 25.2 | 36.5 | 23.60 |

\(^a\) compressive strength;  
\(^b\) hardness.

Filling UHMWPE with an oil suspension (engine oil, linseed oil) leads to an increase in compressive strength, which proves the effect of a liquid filler on UHMWPE. Hardness is still on initial UHMWPE level.

The tribological properties of nanocomposites were characterized by the friction coefficient and the mass wear rate. The tribological properties of the composites are presented on the Table 2.

| Power of ultrasound, W | UHMWPE + engine oil | UHMWPE + drying oil |
|------------------------|----------------------|---------------------|
| I, mg/h\(^a\) | f\(^b\) | I, mg/h\(^a\) | f\(^b\) |
| 0 | 0.12 | 0.41 | 0 | 0.12 | 0.41 |
| 750 | 0.12 | 0.34 | 750 | 0.06 | 0.37 |
| 1,125 | 0.04 | 0.36 | 1,125 | 0.13 | 0.43 |
| 1,500 | 0.20 | 0.41 | 1,500 | 0.12 | 0.40 |

\(^a\) mass wear rate;  
\(^b\) friction coefficient.
Filling UHMWPE with engine oil at an ultrasonic power of 1,125 W results in a decrease in the rate of mass wear by 3 times, and when filled with drying oil, the wear decreases in a half at an ultrasonic power of 750 W. This is due to the fact that these capacities are optimal for these fillers.

Filling of UHMWPE with ENEOS engine oil leads to a decrease in friction coefficient by 17% and 12% with an ultrasonic power of 750 and 1,125 W. UHMWPE filled with drying oil reduces the friction coefficient by 10% with an ultrasonic power of 750 watts. This is due to the release of lubricating oil from the pores of the composite and the modification of the friction surface due to wetting of the UHMWPE with oil.

To describe wearing and friction mechanisms IR spectroscopy of composites surfaces were conducted. The spectra are presented in the Figure 1.

As it can be seen from IR spectra, many chemical changes occur during friction. The PCM samples after friction manifest themselves by the bands at 1050 and 1163 cm\(^{-1}\) (C–O bonds) and broad band in the region 1750 – 1500 cm\(^{-1}\), indicating the formation of ketone groups [7]. It is also confirmed by the band at 1428 cm\(^{-1}\) which corresponds to the \(\alpha\)-CH\(_2\) of oxo group.

Ratio between area of peaks in the region 1500 – 1850 cm\(^{-1}\) and peaks in the region 1450 – 1500 cm\(^{-1}\) to evaluate oxidation of the composite surface during friction. Band in the region of 1475 cm\(^{-1}\) corresponds to the CH\(_2\) group and it was taken as standard. Results of calculations are shown in the Table 3.

### Table 3. Evaluation of the oxidation of composites surfaces.

| Liquid filler | Surface state  | 750 W | 1,125 W | 1,500 W |
|---------------|---------------|-------|---------|---------|
| Drying oil    | Before friction | 0,20  | 0,20    | 0,10    |
|               | After friction | 3,36  | 5,80    | 1,90    |
| Engine oil    | Before friction | 0,08  | 0,12    | 0,07    |
|               | After friction | 0,51  | 2,00    | 0,51    |

All composites during friction are oxidized due to the ambient oxygen and friction heat. However, the use of engine oil leads to the less oxidation of the polymer on the friction surface (Figure 2).
The use of engine oil leads to decrease of oxidation processes intensity (Figure 2, b). It can be explained by decrease of friction coefficient due to the escape of the incapsulated oil from the UHMWPE pores during friction.

4. Conclusion
The tribotechnical properties of nanocomposites were characterized by the friction coefficient and the rate of mass wear. The filling of UHMWPE with ENEOS engine oil leads to a decrease in friction coefficient by 17% and 12% with an ultrasonic power of 750 and 1,125 W respectively. This is due to the escape of lubricating oil from the pores of the composite and the modification of the friction surface due to wetting of the UHMWPE with oil.

The mass wear rate of UHMWPE filled with ENEOS engine oil at an ultrasonic power of 1,125 W reduces by 3 times; when filled with drying oil, the wear decreases in a half with an ultrasonic power of 750 W. This is due to the fact that these powers are optimal for these fillers.

The method of infrared spectroscopy showed that the use of engine oil leads to a decrease of oxidation processes intensity.

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References
[1] Kalia S and Fu S-Y 2013 Polymers at cryogenic temperatures vol 9783642353352 (Berlin: Springer-Verlag Berlin Heidelberg) p 292
[2] Paul D R and Robeson L M 2008 Polymer 49 3187–204
[3] Wu G, Zhao C-H and Zhao X-Z 2008 J. Clin. Rehabil. Tissue Eng. Res. 12 8893–6
[4] Petrova P N, Fedorov A L and Okhlopkova A A 2016 Russ. Eng. Res. 36 371–5
[5] Petrova P N, Okhlopkova A A and Fedorov A L 2015 J. Fric. Wear 36 9–14
[6] Okhlopkova T A, Borisova R V, Nikiforov L A, Spiridonov A M, Sharin P P and Okhlopkova A A 2016 Russ. J. Appl. Chem. 89 1469–76
[7] Nakanishi K 1962 Infrared absorption spectroscopy: practical (San Francisco, CA: Holden-Day) p 243