Frontiers in Mechanochemistry and Mechanical Alloying
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INCOME2008
1-4 December, 2008

BALL MILLING EFFECT ON THE PROPERTIES OF ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE - BRONZE COMPOSITE

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Keywords: Polymer-based composite, Mechanical properties, Tribology

Abstract

Peculiarities of the technology to produce a composite material based on ultra-high molecular weight polyethylene (UHMWPE), mechanically activated with bronze powder are considered along with the properties of the produced material. Samples of the press-composition on the basis of UHMWPE with 0 up to 97.5% of the bronze powder addition were prepared by joint mechanoactivation of super-high-molecular polymer and the bronze powder using planetary mechanoactivator MPF-1 and toroidal vibration mechanoactivator MV-0.05. Packed density of the press-composition was analyzed as a function of the formula and the mechanoactivation technique used. Bulk samples for the tests were obtained by direct pressing. The properties of the samples were studied, and the relations between the density of the material, the physical and mechanical and thermal-physical properties and the concentration of the bronze powder in the material and the milling time were investigated.

Introduction

Advantages in technology are not possible without developing new polymer matrix composites which are widely used as constructional and tribotechnical materials as a substitute for traditional ferrous and nonferrous alloys. Polymer composites are expected to play an important role in reduction of material consumption of machines and mechanisms and in an increase of their reliability and durability. Low cost and commercial accessibility of thermoplastic polymers and dispersed powder fillers, as well as the possibility of traditional technologies and equipment for polymer-matrix composites fabrication ensure high efficiency of their production and application.

Development of promising polymer-matrix composites should be based on the analysis of their operation conditions. The materials under consideration are proposed for the use in the friction units as the bearing and sealing constructions, for example, of rotary-piston machines. The elements of these friction units do not undergo the impact loads and composite materials for them can be modified by spherical particle strengtheners without the use of expensive fibrous materials. This is made possible by using high-energy ball milling, which may be a suitable technique for the synthesis of polymer composites [1-3].

To design polymer-based composite, the polymeric matrix and filler (particles of the strengthened phase) should be selected. In our case, polymeric matrix should possess high (or sufficient) mechanical strength, resistance against aggressive environment, high antifriction properties, sufficient thermal stability and wear resistance. Ultra-high molecular weight polyethylene (UHMWPE) was selected as the matrix material in our study. This polymer, due to its low friction coefficient and high wear resistance, high chemical stability, self-lubrication and high impact resistance properties, is frequently proposed as matrix for the composites [4,5]. Moreover, because of compatibility with human tissue, UHMWPE and composites based on it are widely proposed for prostheses in human joints [6-8].

Filler should be characterized by higher hardness and strength than matrix material, high antifriction properties, high thermal conductivity, and satisfactory adhesion to the matrix material. Use of bronze, because of its good anti-frictional properties and high adhesion to polymer matrix is reported as a filler material in polytetrafluoroethylene as a matrix material in most studies [9-11]. Here the mechanical and tribological properties of the UHMWPE/bronze composites are investigated.

Experimental

The powder of UHMWPE (GUR, Ticona GmbH, Germany) was used as a starting material. The molecular weight of UHMWPE was $3–6\times10^6$ g/mol and its melting point was of 152 ^{0}C. BPK bronze powder of 48-08-09-7-85 type was used as the filler. The composition of the bronze powder was as follows : Cu - 82.8 wt %, Sn - 16.5 wt. %, Fe - 0.39 wt. %, lubricant - 0.3 wt. %.

Powder composites were prepared by ball-milling of UHMWPE and bronze powders together in a MPF-1 planetary ball mill and a MV-0.05 toroidal vibratory mill. The milling time was chosen in such a way that the energy per unit of material was approximately the same for both the mills, namely 30 min for planetary mill and 24 h for vibratory mill.

As-milled composite powders were loaded into the press-form for consolidation. The assembled press-form was put on the plates of the press with electric heating and heated up to a temperature of 150-160 ºC under a pressure of 25 MPa. It was

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hold at this temperature for the time calculated on the basis of 2.0-3.0 min per 1 mm of part thickness. Then the heating was switched off and the press-form was cooled down with water. The press-form was disassembled, and the samples were recovered at a temperature not higher than 60 ºC.

Tension tests of the samples were carried out using standard methods. Not less that 5 samples were taken for each test. They were conditioned before testing for not less than 16 hours at the temperature of 296±2K (23±2ºC) and relative humidity of 50±5 %. The tests were performed using INSTRON test machines that provide load measurement with an relative error of not more than 1%.

The tribologocal tests were performed using an original IMASH RAS test bed that allows one to study the operation of materials in dry sliding-friction mode which usually is realized in sealing units of various machines and devices. Figure 1 shows the schematic of a frictional unit in a setup for tribotecnical tests.

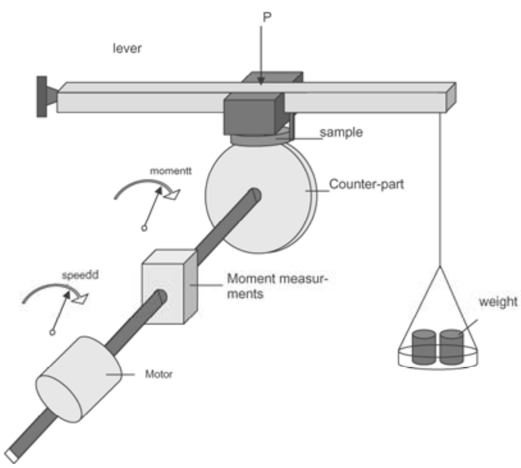

Figure 1. Scheme of tribotechnical tests setup

We used plain samples ~15 mm in diameter, and 4 mm in thickness; face side of the samples was used as frictional surface. As a counterpart, we used a sleeve sample made of 40Kh steel whose hardness at the friction surface was HRC 55. The outside diameter of the sample was D = 0.1 m; it cylindrical surface was polished to an average roughness parameter R_z = 3.5-4.5 µm. The sliding velocity on the friction surface of the sleeve sample was 2.56 m/s, The loading P was varied from 7 to 19 N. The contact friction coefficient was calculated by the expression

$$f = \frac{2M}{D.P}$$

where M is the moment of friction, N·m, and P is a load, N. The wear intensity was calculated by the expression

$$I = \frac{\Delta h}{L}$$

where Δh is the linear wear of the sample material at each stage of loading; $L = \pi.D.n.t$ is the friction path at each stage of loading; and n is the rotation frequency of the counterpart.

Results and Discussion

To investigate the effect of milling process on the mechanical properties of pure UHMWPE, milled for 30 min in planetary ball mill. Samples for tension tests were consolidated by the above-described technique. Results of the mechanical tests are given in Fig. 2. As it is seen, the milling process can affect the properties of the polymer, and that most probably is connected to the processes of mechanodestruction that take place in the process of mechanoactivation of the polymer. Mechano-activation results in the changes in the properties of the polymers: reduction of the molecular mass, reduction of the flow point and specific pressure of the pressing; besides, the destruction processes in the polymer and chemical interaction with the filler are also possible. All this results into the situation wherein the processing technology for such polymer composite materials can differ from the processing technology for the unmilled polymers.

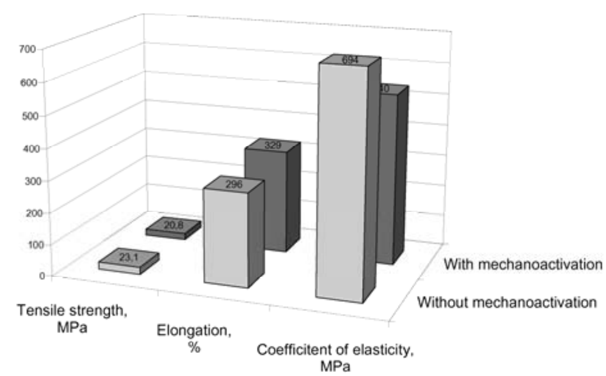

Figure 2. Effect of milling on the mechanical the properties of pure UHMWPE at stretching

Composite samples were consolidated using the same molds as used for the polymer alone. The dependence of the packed density of the press-composition on the way of production and on the time of mechanoactivation in the planetary and vibration mills is shown in Fig. 3 and 4. It was found that if the content of the bronze powder is up to 50 wt. %, the packed density practically does not depend on the method of mechanoactivation. When the content of the bronze powder is higher than 50%, the press-composition produced using vibration mill has a higher packed density than that of the composites produced by planetary mill. Increase in the milling time results in the decrease in the packed density of the material by 2–2.5 times, and after about 30 min of milling this magnitude reaches the plateau. This is the time that practically provides the stable properties of the produced composition. So, the milling longer than 30 minutes is not required.

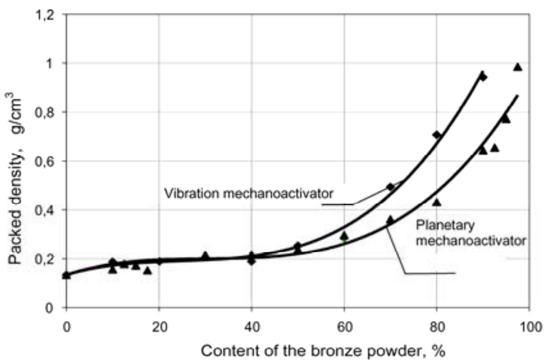

Figure 3. Packed density of the UHMWPE-based composites milled for 30 min in the planetary mill and for 24 h in the vibration mill as a function of the bronze powder content

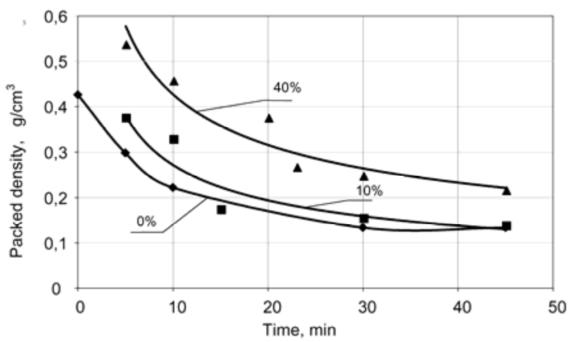

Figure 4.: Packed density of the composition with different concentration of the bronze powder (0, 10 and 40 wt. %) as a function of milling time in the planetary mill

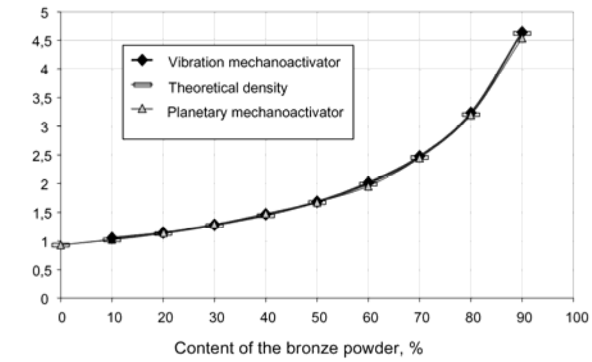

Figure 5. Calculated and actual densities of the consolidated samples prepared by milling using milling during 30 min at the planetary mill and 24 h at the vibration mill as a function of the bronze powder content

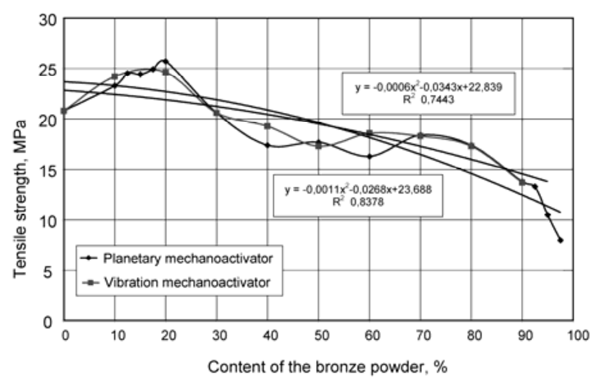

Figure 6. σ_{pp} as a function of the bronze content

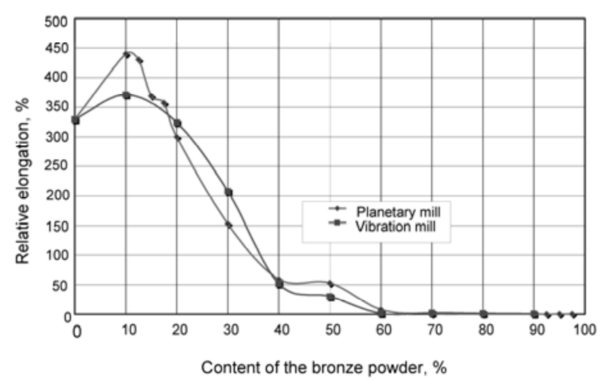

Figure 7. ε_{pp} as a function of the bronze content

To study the concentration dependencies of the properties, the UHMWPE-bronze composites were prepared by milling using planetary mill MPF-1 (during 30 min) and toroidal vibration mill MV-0.05 (during 24 h). As it is seen from Fig. 5, the way of material preparation (30 min at the planetary mill or 24 h at the vibration mill) has nearly no effect on the final density of the composite material, at that the actual density of the samples is almost identical to the theoretical density of the composite.

Figure 6 and 7 show the dependences between mechanical properties of the composite at stretching and the concentration of the bronze powder. The effect of the milling mode on the properties of the ready material was evaluated. Analyzing the concentration dependence of σ_{pp} and ε_{pp} one can see that they have rather pronounced extremes. Maximum tensions are observed at 10 – 20 wt. % of the bronze filler. The dependences of strength of the content of bronze powder are similar both for the planetary and vibratory mills. The range from 10 to 20 % content of the bronze powder is important for the relative elongation at rupture. Coefficient of elasticity E_p, (Fig. 8) increases from about 500 MPa to 3500 MPa and higher with the growth of the content of bronze powder. Though the curves reveal extremes, the obtained dependences can be approximated by similar exponential curves for both planetary and vibration mills.

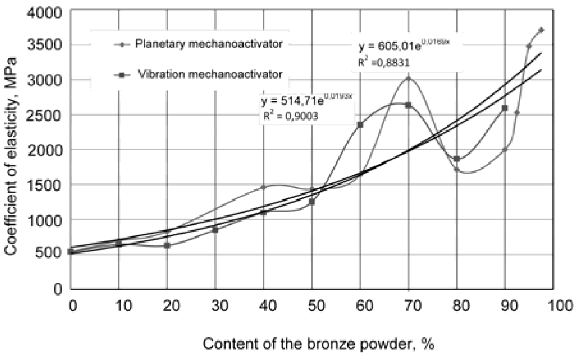

Figure 8. E_p as a function of the bronze content

A study of tribological characteristics was performed in the dry friction mode, which is extreme operation of bearing and sealing constructions of various mechanisms. From the results of tests, the friction coefficient *f*, intensity of the wear *I* (the ratio of the thickness of the worn layer to the friction path), and the microhardness *H* of rubbing surface were determined for each sample. Figure 9 shows the dependence of the friction coefficient on the applied loading. As it follows from Fig. 9, the optimal concentration of filler, for which the minimum coefficients of friction are obtained, is 20 and 10 wt. % for the composites prepared using planetary and vibratory mill, respectively. For the unfilled UHMWPE the friction coefficients exceed the above mentioned minimum by 1.6 - 2 times, at that the friction coefficient of sample produced by consolidation of initial UHMWPE powder is considerably higher than for the sample produced of pure ball-milled UHMWPE. Figure 10 shows an evolution of the friction coefficient, wear and microhardness of samples with increasing filler content, measured at maximum used loading of 19 N. Wear of samples gradually decreases with increasing filler content; at that the microhardness of sample surface increases. The samples prepared using the vibratory mill exhibit lower wear, micohardness and friction coefficient than the samples prepared by planetary mill.

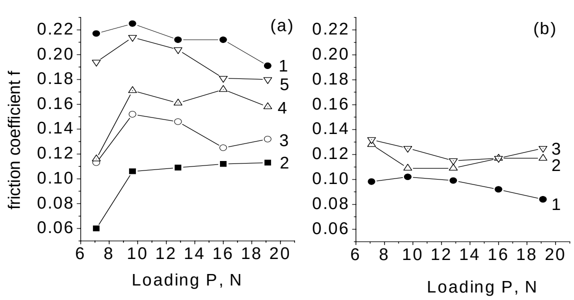

Figure 9. Dependences of friction coefficient on the applying loading: (a) samples milled in planetary mill with bronze content of 0 (4), 10 (1), 20(2) and 40 (3) wt. %. Curve (5) corresponds to the unmilled UHMWPE; (b) samples milled in vibratory mill with bronze content of 10 (1), 20 (2) and 30 wt. % (3).

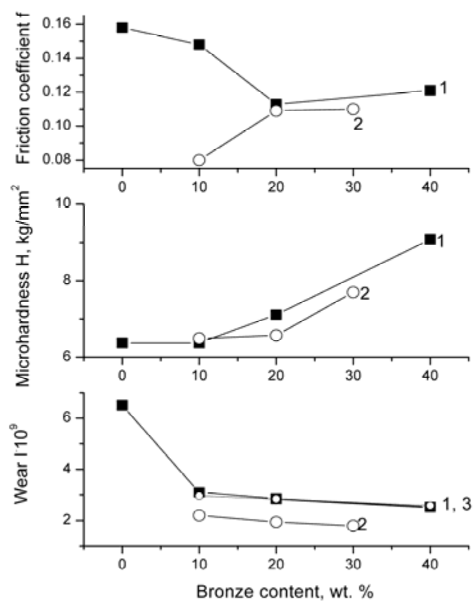

Figure 10. Dependences of friction coefficient, microhardness, and wear at loading of 19 N for samples milled in (1) planetary and (2) vibratory mills on the filler content in the sample. (3) - calculated data for samples, prepared by planetary ball mill

Contact and friction interaction of investigated composite samples with the counterpart surface, as this follows from the analysis of experimental data, can be described using the molecular-mechanical theory of friction and wear. Friction interaction provides the wear of composite in the form of typical surface destruction. It is obvious that the wear of composites is a result of both adhesive and deformation interactions. The typical evidence of the deformation processes, as shown in Fig. 11, is inflation before the revolving counterpart and reduction in the surface profile after the counterpart [12]. Such alternating deformation of surface leads to the friction contact fatigue. This type of contact is more pronounced for unfilled samples, but can also be observed for some filled one. For the majority of tested samples, it is possible to consider elastic deformation as predominant form of friction interaction and destruction of friction connections since stress and strain on the real contacts did not exceed the maximum destructive strength characteristics of material.

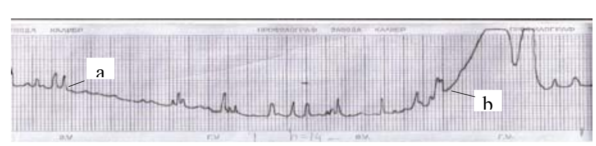

Figure 11. Profilomertic curve of the contact surface for sample, containing 10 wt. % of bronze prepared using planetary mill. Distance between a and b points is 5 mm, maximal decrease of the surface profile in contact zone is 14 µm. The inflation of surface is seen on the right side from the b point

Fatigue wear under plastic deformation was observed during testing of the samples, prepared using the vibratory ball mill, in the case of the maximum loading. During the subsequent tests this form of interaction transformed into the elastic deformation of composite contact with the counterpart surface. The appearance of “microcutting” was observed as a result of introduction of irregularities of counterpart surface into the composite sample. Within the framework of described forms of contact and friction interaction, the estimation of composites wear intensity is based on calculating physicomechanical properties of the material of the surface, parameters of roughness of counterpart surface, etc [13].

Analysis of experimental data shows that wear of such composites may be determined by the following parameters: contact pressure *P*, friction coefficient *f*, surface hardness *H*, the average values *R* and *r* of the maximum height of irregularities and radius of curvature of the roughness peaks, respectively, the parameters of the power approximation of the supporting curve initial part b and ν. Wear intensity *I* for studied samples can be satisfactory described by the following equation:

$$I = 11.3 \cdot 10^{-7} \left(\frac{R}{r \cdot b^{\frac{1}{\nu}}} \right)^{n} \cdot \frac{(P\sqrt{1+f^{2}})^{0,5}}{H^{0,52}}$$

Where the criteria, $\left(\frac{R}{r \cdot b^{\frac{1}{\nu}}} \right)^{n} = 0{,}0158$ was calculated

from the parameters of the counterpart surface roughness, which were measured by profilographing. As it is seen from Fig. 6, calculated values of *I* agree with the experimental data.

Conclusions

The experimental data obtained indicate that, using high-energy ball-milling it is possible to optimize the structure of polymer-based composite material and its mechanical and tribological characteristics for extreme wear conditions.

Based on the generalization of the results of mechanical and tribotechnical tests, the criteria of dependence of the intensity of the wear of composites on the contact pressure, microhardness of the worn out surface of composite, parameter of the calculation of the influence of frictional forces on the wear and the parameter, which characterizes the roughness of the counterpart are determined. Designed materials can be promising for application as bearing supports and sealing units of rotary-piston and other machines.

Acknowledgements

This study was supported by ISTC project 3414.

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