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Optimal Material Selection for Polymer–Polymer Prosthetic Implants by Tribological Criteria

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Abstract—A polymer–polymer tribological pair made of antifriction ultrahigh molecular weight polyethylene (UHMWPE) and high-strength polyetheretherketone (PEEK) composites was proposed and tested in various operating conditions (lubrication medium and dry friction at a deficit of synovial fluid in the joint). The selection of fillers for UHMWPE and PEEK was substantiated in steps proceeding from the data of systematic mechanical and tribological tests. The optimal composition of the composites, suggesting the possibility of manufacturing customized joint prosthetic implants using additive manufacturing technologies, is determined. It was shown that the PEEK (pin)-on-UHMWPE (disk) tribological pair is well compatible, characterized by a low coefficient of friction ($f = 0.02$), and zero wear found by optical microscopy observations. The friction of non-filled UHMWPE on PEEK reinforced with two types of carbon fibers (milled carbon fibers, 30 wt % and CNT, 2.5 wt %) is checked. It is shown that carbon nanotubes are efficient fillers for PEEK in the UHMWPE–PEEK tribological pair under dry sliding friction at a deficiency of synovial fluid.

Keywords: prosthetic implant, ultrahigh molecular weight polyethylene, polyetheretherketone, wear factor, coefficient of friction, elastic modulus, boundary lubrication, thermal conductivity, tribological testing

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INTRODUCTION

Despite the fact that the application of metal–ceramic, ceramic–polymer, and ceramic–ceramic joint prostheses has recently been a topic of active discussions, the most widespread kind of these prostheses is metal polymeric joint implants, in particular, hip joint prostheses with a metal head and a ultrahigh molecular polyethylene (UHWMPE) cap. First of all, these prostheses are used for hip prosthetic repairs [4–6]. The key prerequisites for creating polymer–polymer prosthetic implants are the emergence of high-strength thermoplastics and derive composites; development of additive technologies for making polymeric items from these plastics and composites; development of methods of computer simulation and designing of polymeric composites and friction pairs on their basis [1–3].

The application of nonpolymeric parts in prosthetic implants has usually been justified by the low wear resistance of UHWMPE, inevitable accumulation, and encapsulation of wear particles as well as slacking of polymeric implants, which stimulates their replacement with more solid materials [7, 8]. However, in addition to a low friction coefficient, using the polymeric component ensures the execution of other functions. Thus, relatively low elasticity module and polymeric material viscosity favor impact load damping. Unlike their metallic counterparts, the wear particles of biocompatible polymers do not cause any inflammation in the human body. Therefore, the topics discussed in the literature are combinations of hard and soft contact bodies (soft bearings: Metal-on-Polymer, MoP; Ceramic-on-Polymer, CoP) or hard and hard contact bodies (hard bearings) (Ceramic-on-Ceramic, CoC; Metal-on-Metal, MoM; Ceramic-on Metal, CoM) [9, 10].

In addition, the development of prostheses is aimed to ensure their deformation compatibility with neighboring biological tissues, first of all, similarity of the elasticity modules of prosthetic and replaced materials or the optimal gradient of their elasticity module in the near-contact region [11]. In this context, the hard–hard combination for artificial limbs can damage the adhesive prosthesis-bone junction and initiate a process known as loosening. A broader range of materials for tribological couplings is studied in [12, 13], where the prospects of using polyether ether keton (PEEK) in orthopedy are discussed. Certain achievements in the domain of healthcare material science have caused the market appearance of Optima PEEK; this PEEK is considered a substitute for the metal heads of artificial joints paired with UHWMPE caps [14] similarly to the prosthetic repairs of neck vertebrae [15–17].

The specified literary data are indicative of the expanding use of polymer–polymer friction units due to the development of new high-strength and high-temperature thermoplastics. In soft bearings, high-strength polymers can replace metal and ceramics in which case their carrying capacity can be additionally improved by using a reinforcing filler, for example, carbon fibers. In the light of rapidly developing additive technologies, using thermoplastic biocompatible polymers in making artificial limbs is also a promising solution. According to the aforesaid, the optimal choice of materials for polymer–polymer prosthetic implants is an efficient solution for the considered relevant issue.

Objective—To search for consumable polymeric materials for making artificial polymer–polymer joints by additive technologies.

MATERIALS AND METHODS

The powder used in this study was German-made UHWMPE Ticona GUR-2122 powder with a molecular weight of 4.5 million, UK-made PEEK Victrex 450PF powder with an average particle size of 50 μm. The compounds used as fillers were Taunit carbon nanofibers (CNFs) (∅ = 60 nm, l = 2–3 μm) made in Tambov by OOO Nanotechcenter, Tuball carbon nanotubes (CNTs) (∅ = 10 nm) made in Novosibirsk by OCSiAl, ground carbon microfibers (GCMFs) (l = 45 μm, ∅ = 10 μm) made in Chelyabinsk by OOO ZUKM, chopper carbon fibers (CCFs) (l = 2 mm, ∅ = 10 μm) made in Chelyabinsk by OOO ZUKM, and C-1 colloidal graphite with a particle size of 1–4 μm made in Chelyabinsk by OOO Graphite Service.

The 3D workpieces of polymeric composites were made by compressive caking of UHWMPE powder mix at a pressure of 10 MPa and a temperature of 200°C and PEEK powder mix at a pressure of 15 mPa and a temperature of 400°C. The workpieces were made on a lab facility based on an MC-500 hydraulic press made in Moscow by OOO NPK Techmash. The facility was equipped with a cutoff annular furnace. The workpieces were cooled without depressurizing at a rate of 2°C/min.

The wear tests under dry friction and boundary lubrication were conducted according to the pin-on-disk pattern on a Swiss CSEM CH2000 tribometer. The boundary friction in use was saline solution (water solution of sodium chloride (NaCl) with mass fraction ω of NaCl ≈ 0.9%. For the tribological test parameters see Table 1.

Table 1. Parameters of the tribological tests according to the pin-on-disk pattern

Pin diameter, mm	3
Contact area, mm^2	7.07
Load, N	15
Contact pressure, MPa	1.4
Sliding speed, m/s	0.45
Distance (friction course), m	5000

The friction pairs used during the tests were PEEK-on-PEEK, UHWMPE-on-UHWMPE, and UHWMPE-on-PEEK. The linear wear of the specimens (pins) was determined by the change in their linear dimensions with the help of a micrometer with a measurement accuracy of 0.01 mm. The volumetric wear of the disk was determined by the friction track depth on a US-made Alpha-Step IQ contact profile meter (KLA-Tencor).

The wear tests under dry friction and boundary lubrication were conducted according to the shaft-pad pattern on a 2070 SMT-1 friction machine (Tochpribor PA, Ivanovo) only for the UHWMPE-PEEK pair at a load of 40 N, sliding speed of 0.3 m/s, and friction track of 1000 m. The diameter of the counterbody (shaft) from PEEK and the derived composites was 35 mm. The dimensions of the prismatic pad from UHWMPE were 16 × 10 × 8 mm.

The surface of the test specimens was checked using an New View 6200 optical profile meter (Zygo, United States).

RESULTS AND DISCUSSION

Selection of Compatible Polymeric Materials for Friction Pairs

The text below describes the step-by-step selection of the optimal friction pair by tribological tests of model components under dry friction and lubrication. The selection involved using various combinations of mated components from hot-pressed UHWMPE and PEEK.

Tribological Tests of Non-Filled Polymers Molded by Hot Pressing. Pin-on-Disk Pattern

The results of the tests are presented in Fig. 1a in wear factor (WF) units. It is seen that the highest wear factor (WF) under dry friction is WF = 1.29 × 10^{-4} mm^3/(N m) and it is typical for the homonymous UHWMPE-on-UHWMPE friction pair. During the tribological test under boundary friction the WF of this friction pair decreased by 16-fold in comparison

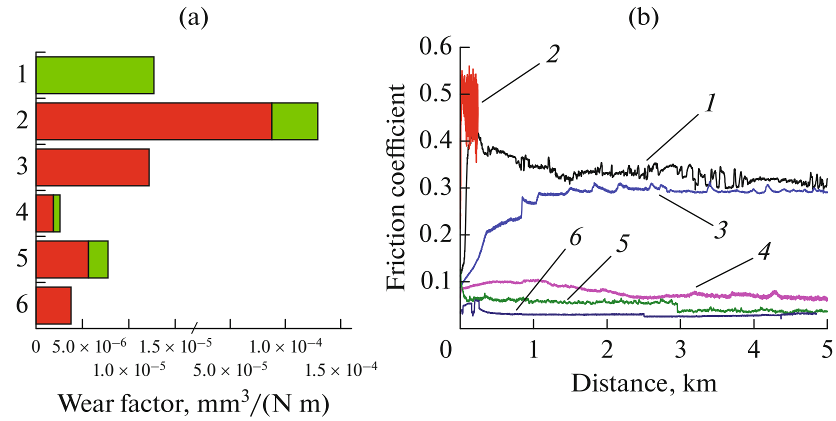

Fig. 1. Wear factor (a) and the dependences of the friction coefficients on the sliding distance (b) of polymer–polymer friction pairs at dry sliding friction and boundary lubrication: (*1*) for PEEK on PEEK (dry friction); (*2*) for UHMWPE on UHWMPE (dry friction); (*3*) for UHWMPE on PEEK (dry friction); (*4*) for PEEK on PEEK (boundary lubrication); (*5*) for UHWMPE on UHWMPE (boundary lubrication); and (*6*) is for UHMWPE on PEEK (boundary lubrication).

with the test under dry friction and reached 7.76 × 10^{-6} mm^3/(N m). The comparable WF of the PEEK-on-PEEK and UHWMPE-on-PEEK friction pairs under dry friction was WF = 1.22–1.27 × 10^{-5} mm^3/(N m). The WF under boundary friction was 3–4-fold lower and reached 2.59–3.77 × 10^{-6} mm^3/(N m).

The kinetics of change in the friction coefficients over time in the polymer–polymer tribological couplings under dry friction and boundary lubrication is presented in Fig. 1b. It is seen that in the homonymous UHWMPE-on-UHWMPE coupling the friction coefficient is f = 0.47 ± 0.04. This very high value is determined by intensive frictional heating encouraged by a fairly high initial friction coefficient. According to the measurement data, the maximal temperature at sliding is 150°C, which exceeds the UHWMPE melting temperature (135°C).

It follows from Fig. 1b that the wear factor of the UHWMPE-on-UHWMPE coupling under boundary lubrication is ninefold lower than under dry friction, that is, f = 0.05 ± 0.01. Therefore, the temperature for all friction pairs under friction in the boundary lubrication mode is $T \leq 35$°C.

The dry friction mode of the other homonymous mating (PEEK-on-PEEK) is characterized by f = 0.33 ± 0.03. The high oscillation of the friction coefficient observed for the entire test distance is probably connected with the adhesive bonding of the contact surfaces due to their heating to 190°C. In comparison with the friction coefficient of the PEEK-on-PEEK mating in dry friction mode, its friction coefficient under boundary lubrication decreased by fourfold, that is, f = 0.08 ± 0.01.

In the UHWMPE-on-PEEK heteronymous tribological mating the friction coefficient is f = 0.28 ± 0.04, which is also due to the intensive heating of the materials of the polymer–polymer tribological coupling. The maximal temperature at sliding is 160°C, which is similar to the temperature for the earlier considered UHWMPE-on-UHWMPE combination and significantly exceeds the UHWMPE melting temperature (135°C). The friction coefficient of the UHWMPE-on-PEEK mating under boundary lubrication is f = 0.03 ± 0.01, which is ninefold lower than under dry friction and the minimal value of all attained values.

The micrographs of the friction surfaces after the tribological tests are presented in Fig. 2. In case of the PEEK-on-PEEK pair the carryover of material from the counterbody to the surface of the PEEK pin (Fig. 2a) is observed as well as the grooving on the surface of the PEEK disk along the sliding direction (Fig. 2d), which indicates that the wear pattern is adhesive–abrasive.

In case of the UHWMPE-on-UHWMPE pair (Figs. 2b and 2e), extended overlaps aligned in parallel with the sliding direction are generated on the friction surface. Their generation is determined by the plastic strain induced by the frictional heating of the polymer above the melting temperature.

The generation of overlaps due to the plastic strain and heating of the polymer above the melting temperature is also observed on the friction surface of the UHWMPE pin of the UHWMPE-on-PEEK pair (Fig. 2c); however, the heating is less intensive than in the previous case. The friction surface of the PEEK disk (Fig. 2f) is covered with traces of the carryover of material from the counterbody.

The micrographs of the friction surfaces after the tests under boundary friction are presented in Fig. 3.

The friction surface of the PEEK-on-PEEK pair (Figs. 3a and 3d) is characterized by the generation of microgrooves aligned along the sliding direction. Their length and depth are much smaller than the length and depth of the grooves generated at dry friction (Figs. 2a and 2d). This is determined by the fact

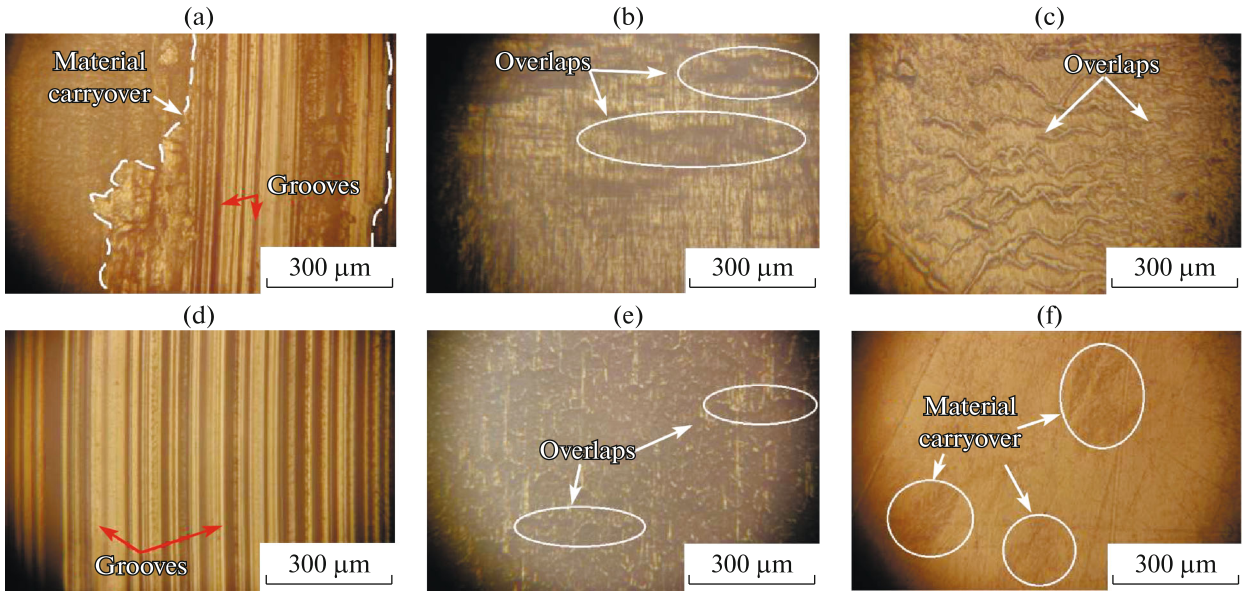

Fig. 2. Micrographs of the wear track surfaces of the PEEK-on-PEEK ((a) is the pin, (d) is the disk); UHMWPE-on-UHMWPE ((b) is the pin, (e) is the disk); UHMWPE-on-PEEK ((c) is the pin, (f) is the disk) tribological couplings at dry sliding friction.

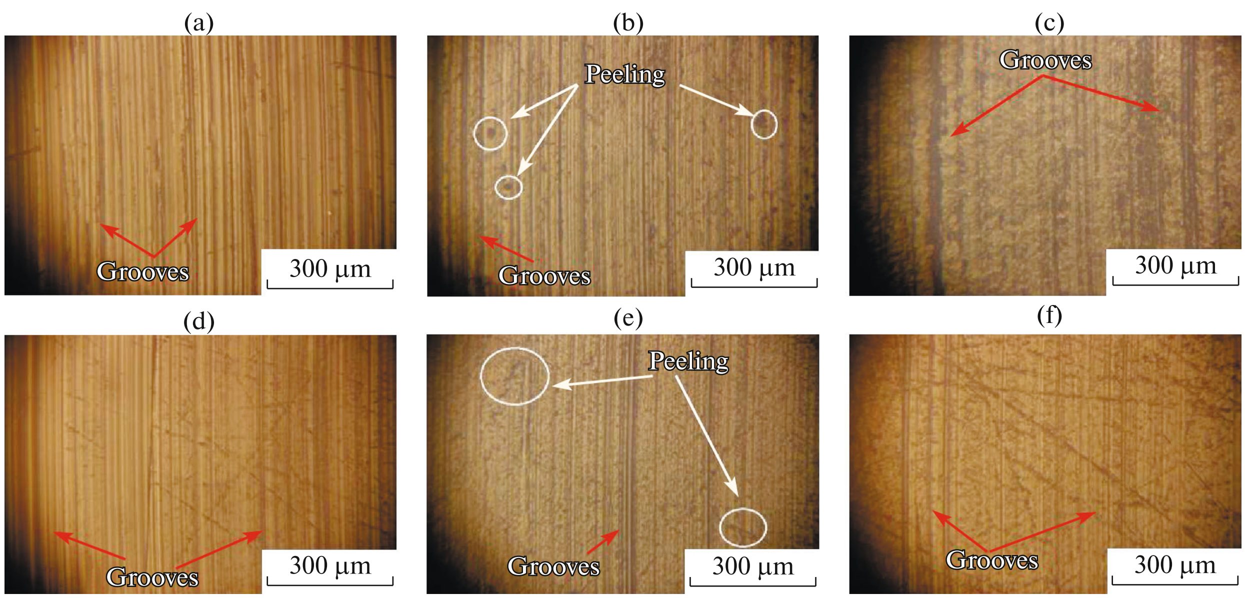

Fig. 3. Micrographs of the PEEK-on-PEEK ((a) is the pin, (d) is the disk); UHMWPE-on-UHMWPE ((b) is the pin, (e) is the disk); UHMWPE-on-PEEK ((c) is the pin, (f) is the disk) tribological couplings at boundary lubrication.

that the wear products are easier to remove from the tribocontact region under boundary friction. A carry-over film is not generated from the wear products of PEEK.

The friction surface of the UHWMPE-on-UHWMPE pair (Figs. 3b and 3e) is characterized by the generation of fatigue damage areas as well as individual grooves in parallel with the sliding direction.

The friction surface of the UHWMPE-on-PEEK pair is also covered with grooves, more regular for UHWMPE and less regular for PEEK. The grooves on the surface of the UHWMPE pin (Fig. 3c) are much deeper and longer than the grooves of the PEEK disk (Fig. 3f). The more intensive abrasive wear of UHWMPE as compared with PEEK is determined by the low hardness of UHWMPE in this tribocoupling.

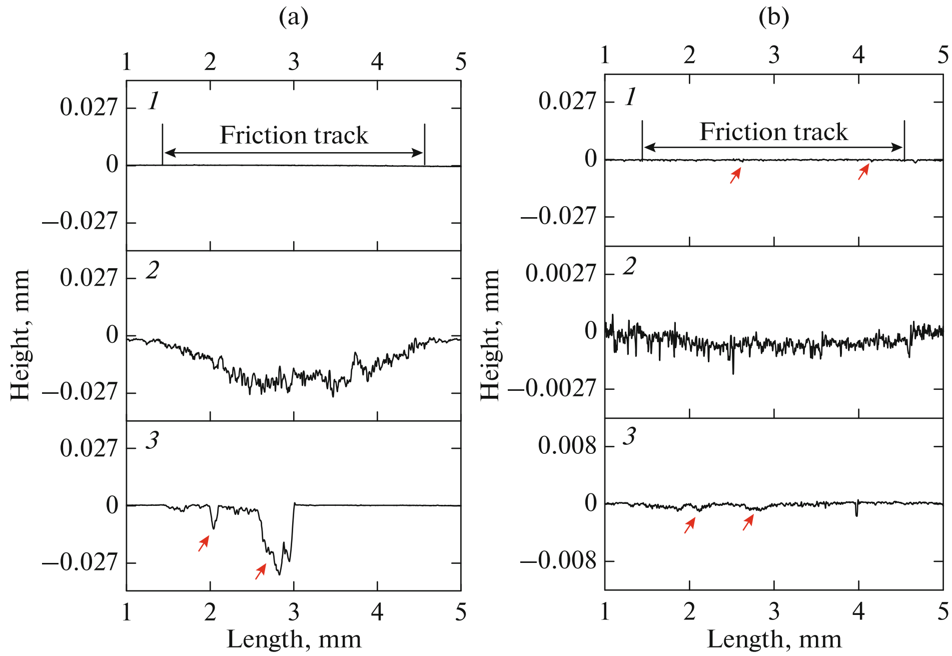

Fig. 4. Friction track profiles after the testing at dry sliding friction (a) and boundary lubrication (b): (*1*) for PEEK-on-UHMWPE; (*2*) for UHMWPE-on-UHMWPE; (*3*) for PEEK-on-PEEK.

For the profile diagrams of the friction tracks of the tested material specimens see Fig. 4. Note that dry friction mode (Fig. 4a) has the following peculiarities:

— The friction track profile during the slide of the softer UHWMPE against the harder PEEK remains unchanged.

— There is a significant change in the friction track profiles of the UHMPE-on-UHWMPE pair.

— The wear of the PEEK disk during friction against the PEEK pin is uneven, and the shaped grooves are characterized by greater depth and width.

On the whole, these regularities also remain in force at boundary lubrication; however, the grooves on the friction track of the homonymous PEEK-on-PEEK pair are not so deep (Fig. 4b).

It follows from the above data that the solutions recommendable for creating polymer–polymer tribo-couplings are the homonymous PEEK-on-PEEK pair or the heteronymous UHWMPE-on-UHWMPE pair in case of substantial flaws, such as the high friction coefficient of nonmodified PEEK and the low strength of UHWMPE.

During tribological tests the homonymous friction pairs are characterized by explicit heating due to the low heat conduction of polymeric materials and the low UHWMPE melting temperature, several degrees as low as the PEEK vitrification temperature.

Thus, the characteristic features of heteronymous friction pairs at preset friction duration and track, in particular, UHWMPE pin–PEEK disk are that UHWMPE exhibit low wear (0.31×10^{-5} mm^3/(N m)) at the actual zero wear of the PEEK disk within the sensitivity range of the method. Ultimately, the PEEK pin-UHWMPE disk tribocoupling is well compatible, has a low friction coefficient ($f = 0.02$), and does not have any visible and registered wear of both materials. The results of the tests were used for a more detailed test of the UHWMPE–PEEK composite pair as the most promising friction pair.

Results of Tribological Tests of UHWMPE-on-PEEK Composite Pair during Dry Friction

Since one of the reasons for the high wear factor during dry friction was a significant rise in the temperature and softening of the materials, it was proposed to modify PEEK with fillers, which would increase their heat conduction and strength. The materials used as these fillers were:

— 30 wt % of ground carbon fiber with an average length of about 45 μm (PEEK/30CF).

— 2.5 wt % of carbon nanofibers (PEEK/2.5CNFs).

— 2.5 wt % of carbon nanotubes (PEEK/2.5CNTs).

— 30 wt % of colloidal graphite (PEEK/30Graphite).

— Mix of 15 wt % of ground carbon fiber with a length of 0.2 mm and 15 wt % of colloidal graphite (PEEK/15CF$_{0.2\,mm}$/15Graphite).

— Mix of 15 wt % of ground carbon fiber with a length of 2 mm and 15 wt % of colloidal graphite (PEEK/15CF$_{2\,mm}$/15Graphite).

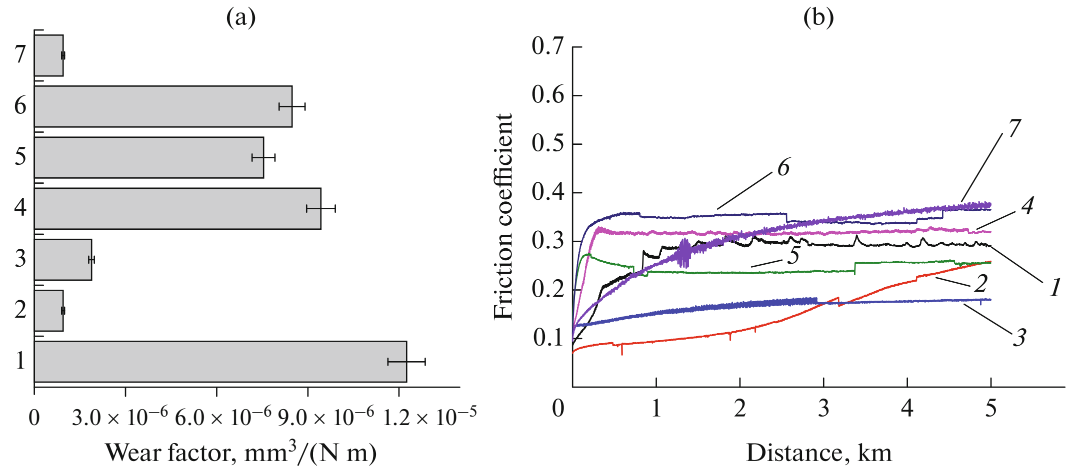

Fig. 5. Wear factor (a) and the dependences of the friction coefficient on the sliding distance (b) for the UHMWPE when tested on PEEK composites under dry sliding friction: (*1*) for UHMWPE-on-PEEK; (*2*) for UHMWPE-on-PEEK/30CF; (*3*) for UHMWPE-on-PEEK/2.5CNT; (*4*) for UHMWPE-on-PEEK/2.5CNF; (*5*) for UHMWPE-on-PEEK/30Graphite; (*6*) for UHMWPE-on- PEEK/15CF$_{2\ mm}$/15Graphite; (*7*) for UHMWPE-on-PEEK/15CF$_{0.2\ mm}$/15Graphite.

The tribological test results are presented in Fig. 5a. It is seen that the highest WF = 1.22×10^{-5} mm^3/(N m) is observed at the friction of filler-free matrix polymeric materials (UHWMPE-on-PEEK).

The WF of the UHWMPE tribocouplings with PEEK/2.5CNF, PEEK/30Graphite, and PEEK/15CF$_{2\ mm}$/15Graphite is by 20–40% lower than the WF of the UHWMPE-on-PEEK pair. The WF of UHWMPE also decreases with the friction against PEEK/2.5CNF (WF = 1.88×10^{-6} mm^3/(N m)). The minimal wear factor of UHWMPE is observed with the friction against PEEK/30CF and PEEK/15CF$_{0.2\ mm}$/15Graphite (WF = 9.43×10^{-7} mm^3/(N m)).

The friction pairs with the low wear factor of the UHWMPE component also had a low friction coefficient. The kinetics of change in the friction coefficients of the polymer–polymer tribocouplings is shown in Fig. 5b and proves that the minimal f of 0.17 ± 0.01 is typical of the UHWMPE-on-PEEK/2.5CNT friction pair. The maximal heating temperature does not exceed 105°C.

In the initial section of the sliding path the friction coefficient of the UHWMPE-on-PEEK/30CF friction pair is only $f = 0.08 \pm 0.01$, which then rises to $f = 0.25$. The increase in the friction coefficient is attended by intensive frictional heating; the maximal tribocontact temperature is 120°C.

The friction coefficient of the UHWMPE-on-PEEK/30Graphite friction pair is $f = 0.25 \pm 0.01$; the maximal heating temperature is 90°C.

Friction coefficients f of the UHWMPE-on-PEEK/2.5CNF, UHWMPE-on-PEEK/15CF$_{2\ mm}$/15Graphite, and UHWMPE-on-PEEK/15UV$_{0.2\ mm}$/15Graphite pairs are 0.30–0.35; the maximal tribocontact temperature is 120–160°C.

The micrographs of the friction surface of the UHWMPE pin after the frictional interaction with PEEK and the derived composites are shown in Fig. 6. Let us note the main regularities:

— The UHWMPE-on-PEEK pair (Fig. 6a) has overlaps on the friction surface, which are caused by plastic strain and frictional heating to 160°C.

— The UHWMPE-on-PEEK/30CF (Fig. 6b) has smaller local overlaps on the friction surface, which are caused by a low friction coefficient and a temperature drop.

— The UHWMPE-on-PEEK/2.5CNT (Fig. 6c) has small grooves along the sliding direction on the UHWMPE friction surface.

— The UHWMPE-on-PEEK/2.5CNT (Fig. 6d) has large overlaps on the UHWMPE surface, which are caused by an increased friction coefficient and derived temperature rise.

— The UHWMPE-on-PEEK/30Graphite, UHWMPE-on-PEEK/15CF$_{2mm}$/15Graphite, and UHWMPE-on-PEEK/15CF$_{0.2mm}$/15Graphite (Figs. 6e–6g) pairs have microabrasive wear on the friction surface, which includes microgrooving in parallel with the sliding course of the counterbody.

The micrographs of the friction surface of the counterbody material (PEEK composites, disk) after the tribological tests are shown in Fig 7. It is seen that:

— On the UHWMPE-on-PEEK pair the PEEK friction surface (Fig. 7a) is smooth, with single traces of UHWMPE.

— On the UHWMPE-on-PEEK/30CF pair (Fig. 7b) the PEEK surface has a lot of irregularities caused by the existence of short carbon fibers.

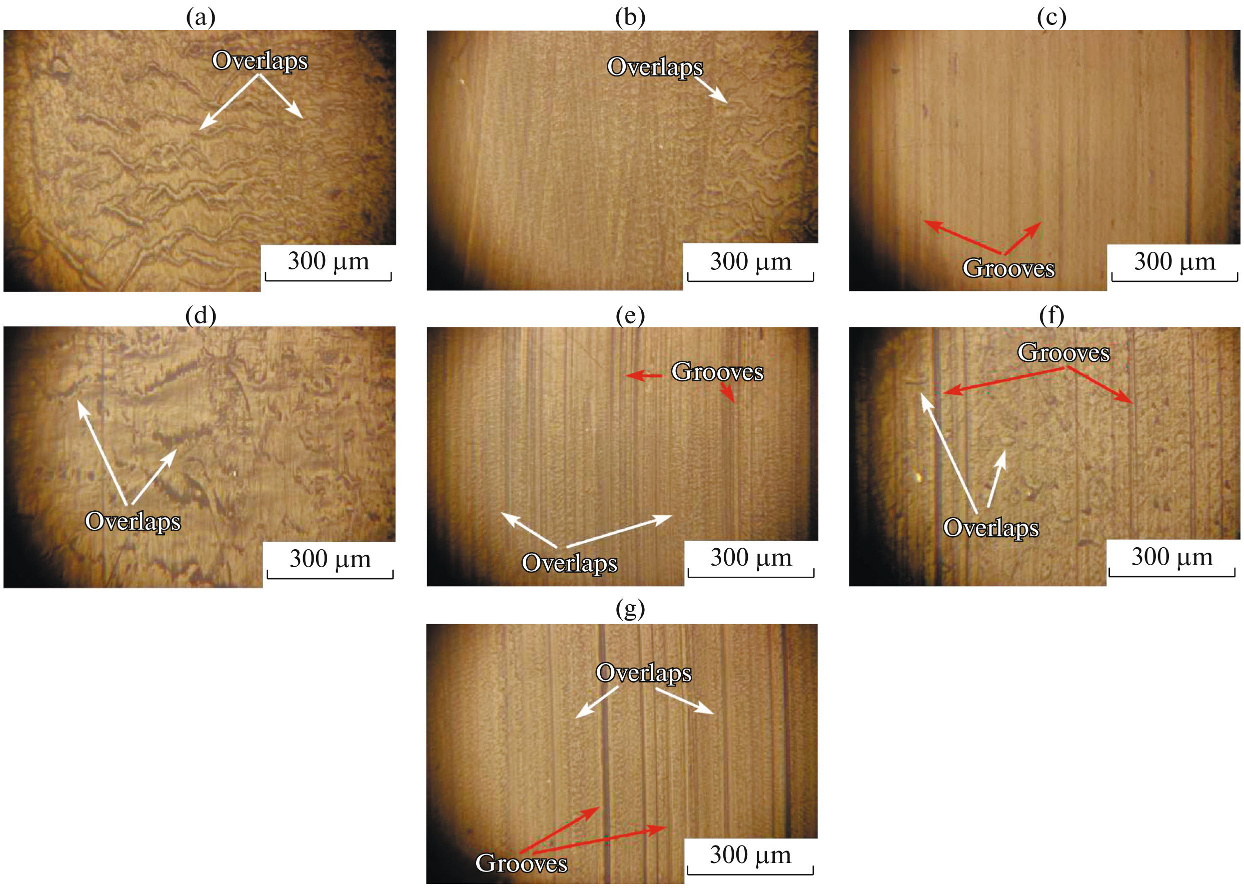

Fig. 6. Micrographs of the wear surface of UHMWPE (pin) under dry sliding friction on PEEK (a); PEEK/30CF (b); PEEK/2.5CNT (c); PEEK/2.5CNF (d); PEEK/30Graphite (e); PEEK/15CF$_{2\,mm}$/15Graphite (f); and PEEK/15CF$_{0.2\,mm}$/15Graphite (g).

— The friction in the UHWMPE-on-PEEK/2.5CNT pair (Fig. 7c) causes an extremely low wear of PEEK.

— The UHWMPE-on-PEEK/2.5CNT friction pair (Fig. 7d) has extended microgrooves and traces of the transferred material of the UHWMPE pin.

— During friction in the UHWMPE-on-PEEK/30Graphite pair (Fig. 7e) multiple micro-grooves are registered on the surface, which is indicative of microabrasive wear.

— During the friction in the UHWMPE-on-PEEK/15CF$_{2\,mm}$/15Graphite and UHWMPE-on-PEEK/15CF$_{0.2\,mm}$/15Graphite friction pairs (Figs. 7e–7g) single microgrooves are detected on the PEEK surface, whereas no visible signs of wear are registered.

The analysis of the profile diagrams of the friction tracks allows making the following conclusions (Fig. 8):

— There is no wear of the PEEK disk in friction against the UHWMPE pin.

— The significant difference in the friction path profiles on the disk from pure PEEK and composite PEEK/30CF is determined not by the wear but by the low quality (high roughness) of the composite surface shaped by tearing out carbon fibers with chipping. This results most probably from an insufficient filler-matrix adhesion.

— PEEK/2.5CNT and PEEK/2.5CNF disks have shallow and narrow grooves on the friction surface.

— Similarly to the PEEK/30CF composite, the friction surfaces of composites PEEK/30Graphite, PEEK/15CF$_{2\,mm}$/15Graphite, and PEEK/15CF$_{0.2\,mm}$/15Graphite with graphite particles have deep and wide grooves on the friction surface.

Thus, the PEEK/30CF and PEEK/2.5CNT composites can be recommended as counterbodies for the UHWMPE-PEEK friction pair.

Results of Tribological Tests of UHWMPE on PEEK Filled with Carbon Fibers in the Shaft-Pad Configuration under Dry Friction and Boundary Lubrication

Since the testing of the UHWMPE-PEEK friction pair in the pin-disk configuration revealed the efficiency of using the PEEK/30CF compound for the

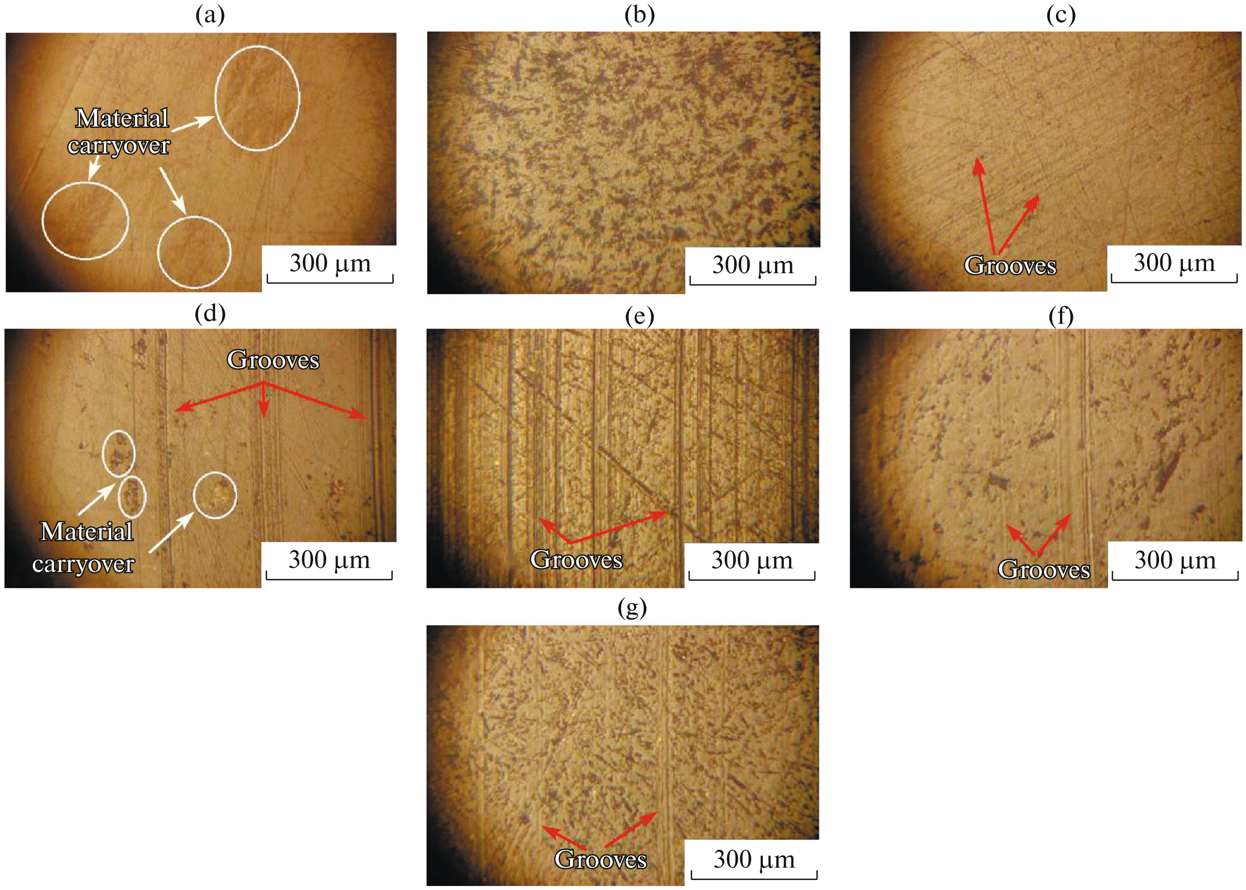

Fig. 7. Micrographs of the disk wear surface: PEEK (a); PEEK/30CF (b); PEEK/2.5CNT (c); PEEK/2.5CNF (d); PEEK/30Graphite (e); PEEK/15CF$_{2\ mm}$/15Graphite (f); and PEEK/15CF$_{0.2\ mm}$/15Graphite (g).

counterbody, several tribological tests were conducted with the shaft-pad configuration of non-filled UHWMPE on PEEK reinforced with two kinds of carbon fiber.

Three friction pair specimens were tested, including UHWMPE-on-PEEK, UHWMPE-on-PEEK + 30 wt % CF40 μm, UHWMPE-on-PEEK + 2.5 wt % CNT. According to the previous section, there is no significant wear of PEEK in the friction of the relatively soft UHWMPE against the harder PEEK and the composites on its basis with micro- and nanocarbon fillers. The volumetric wear of the UHWMPE pad was determined according to the friction track profile with the help of an Alpha-Step IQ contact profile meter.

The profile diagrams of the surface and the roughness parameters of the counterbodies are shown in Fig. 9. The roughness of polymeric counterbodies is equivalent to the roughness of metal bodies, which is $R_a = 0.2$ μm. It is seen that the surface roughness after the tribological tests does not depend on the composite type is comparable in value and does not exceed $R_a \leq 0.27$ μm.

As shown above, the UHWMPE involved in the dry friction on PEEK was exposed to significant heating and the plastic strain caused by this heating. This was why, the shape change was very significant and the wear could not be evaluated. The problem of increasing the heat conduction of the PEEK counterbody was solved by using carbon-containing fillers.

The data on the wear factor of the UHWMPE sliding on the PEEK filled with carbon fiber and nanotubes are presented in Fig. 10. It is seen that the wear resistance of the UHWMPE sliding on the PEEK filled with carbon nanotubes is by 350% higher than the wear resistance of the UHWMPE sliding on the PEEK with carbon nanofibers (WF = 6.5×10^{-6} and 1.45×10^{-6} mm^3/(N m), respectively).

In boundary lubrication conditions, the WF of UHWMPE is similar for both types of fillers for PEEK, which is clearly illustrated in Fig. 10b.

The data on the temperature of the counterbodies (original and filled PEEK) under dry friction and boundary lubrication are shown below (Table 2, Fig. 11). It follows from Table 3 that, first of all, the filling of PEEK with carbon nanotubes at dry friction reduces the temperature by 120% as compared with

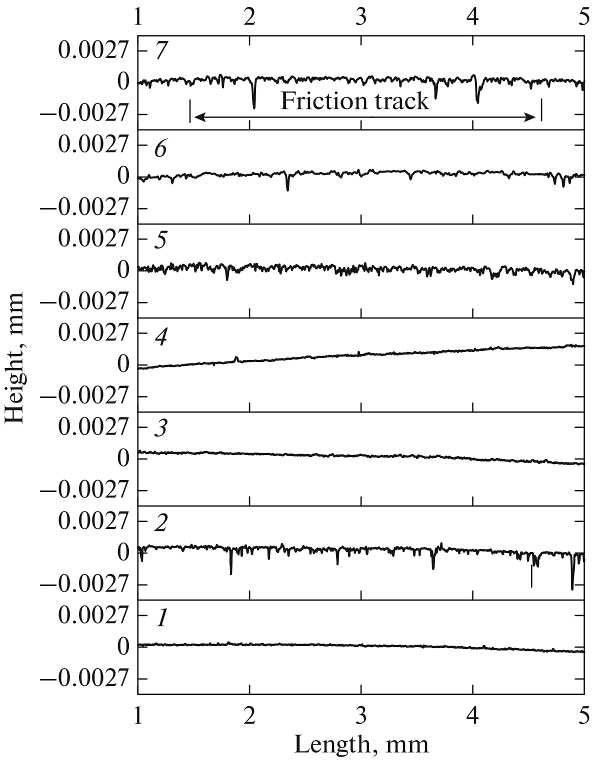

Fig. 8. Friction track profiles after the testing of PEEK composites under dry sliding friction: (*1*) for UHMWPE-on-PEEK; (*2*) for UHMWPE-on-PEEK/30CF; (*3*) for UHMWPE-on-PEEK/2.5CNT; (*4*) for UHMWPE-on-PEEK/2.5CNF; (*5*) for UHMWPE-on-PEEK/30Graphite; (*6*) for UHMWPE-on-PEEK/15CF$_{2\ mm}$/15Graphite; and (*7*) for UHMWPE-on-PEEK/15CF$_{0.2\ mm}$/15Graphite.

the nonmodified PEEK. In this case, the filling with carbon nanofibers reduces the counterbody temperature only by 30%. Secondly, in all of the three cases, the counterbody temperature in the absence of lubricant is similar to the human body temperature.

The photographs of the friction surface of the UHWMPE after the tests under dry friction and boundary lubrication are shown in Fig. 11. In the first case, the test of the UHWMPE-on-PEEK friction pair (Fig. 11a) is attended by the generation of overlaps caused by the plastic strain due to the frictional heating above the UHWMPE melting temperature (the specimen surface temperature is $T \geq 150°C$). In these conditions, the carryover of the material is catastrophic, which is why the surface is generally flat and its roughness determined by the adhesive interaction of the heated materials in contact (Table 2). In case of boundary friction there are only single shallow grooves on the friction surface; however, the surface itself looks sufficiently flat (Fig. 11b).

In the dry friction mode, the contact surface of the UHWMPE pad (Fig. 11c) in the UHWMPE-PEEK + 30 wt % of 40 μm CF combination is covered with riffles shaped as large overlaps with a size exceeding 100 μm. Other registered irregularities are single grooves aligned with the sliding direction. In this case, the temperature is similar to the UHWMPE melting temperature and the indicated overlaps are thermally induced. Considering the fact that the WF as compared with the previous case is much lower, the plasticized material of the surface layer is irreversibly deformed with the generation of a wrinkled surface structure.

In the boundary friction mode, the friction surface is covered with irregular grooves aligned along the counterbody sliding direction (Fig. 11d). The abrasive wear and shaping of these grooves can be caused by the destruction of carbon fibers tracks that are observed on the friction surface of the UHWMPE.

In dry friction mode for UHWMPE-on-PEEK + 2.5 wt % CNT, the UHWMPE surface (Fig. 11e) is covered with overlaps of the plasticized surface layer. However, low temperature (<100°C, Table 2) makes this phenomenon local as well as the grooves aligned with the sliding direction.

In boundary lubrication mode the friction surface is also covered with grooves (Fig. 11f); however, not all of them are parallel-oriented. In this case, the wear factors of the UHWMPE sliding on PEEK nano- and microcomposites are roughly similar (Fig. 10b).

It is therefore reasonable to use carbon fibers and nanotubes as PEEK fillers in the UHWMPE-PEEK friction pair, whereas carbon nanotubes are also effi-

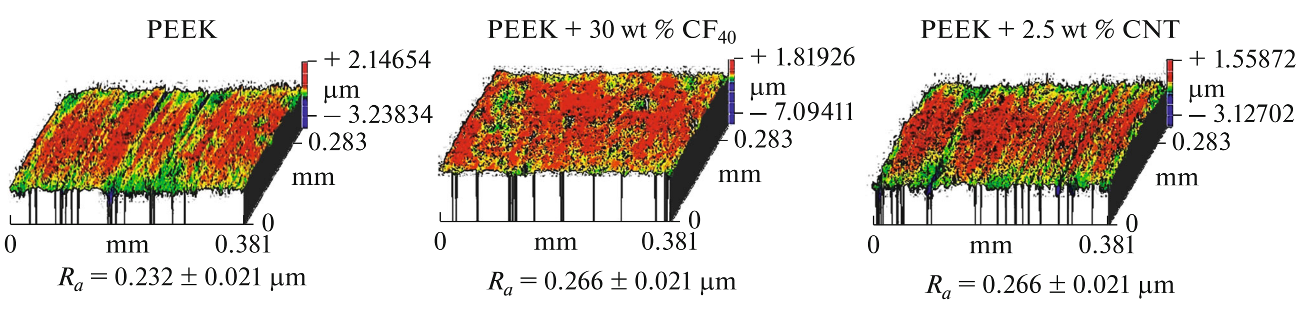

Fig. 9. 3D profiles of surfaces of PEEK and composites PEEK+30 wt % CF (40 μm), PEEK + 2.5 wt % CNT with indicated roughness R_a.

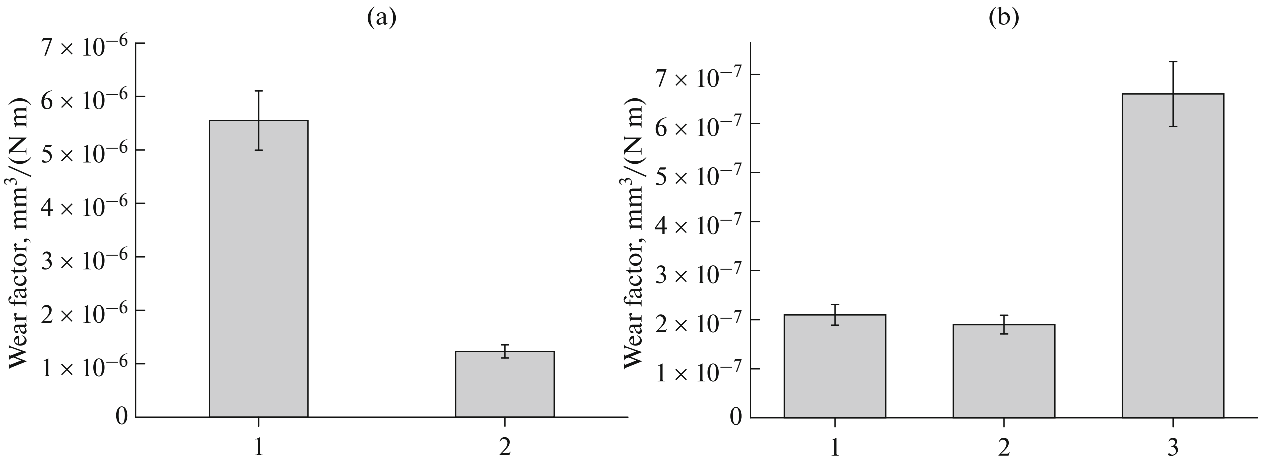

Fig. 10. Wear factor of UHMWPE under sliding friction on PEEK composites at dry friction (a) and boundary lubrication (b) at a load of 40 N and a sliding speed of 0.4 m/s: (1) for PEEK + 30 wt % CF 40 μm; (2) for PEEK + 2.5 wt % CNT; and (3) for PEEK.

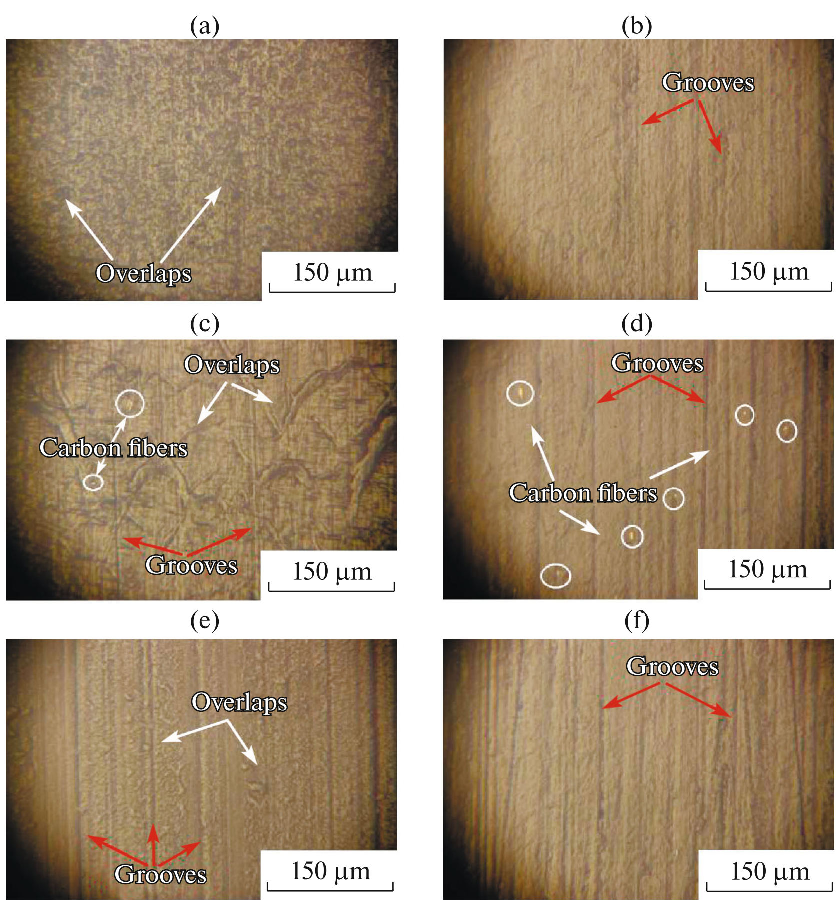

Fig. 11. Micrographs of the wear track surfaces of UHMWPE under friction on PEEK: (a) is for dry friction, (b) is for boundary lubrication; UHMWPE at the friction on PEEK + 30 wt % CF 40 μm: (c) is for dry friction, (d) is for boundary lubrication; UHMWPE on PEEK friction + 2.5 wt % CNTs: (e) is for dry friction, and (f) is for boundary lubrication.

Table 2. Temperature of the counterbody at the tribological testing of PEEK and its composites under dry friction and boundary lubrication at a load of 40 N and a sliding speed of 0.4 m/s

Filler content, wt %	Temperature, °C	
	dry friction	boundary lubrication
Shaft—PEEK Pad—UHWMPE	180	45
Shaft—"PEEK + 30 wt % CF 40 μm" Pad—UHWMPE	126	36
Shaft—"PEEK + 2 wt % CNT" Pad—UHWMPE	81	38

cient at a deficit of synovial fluid in prosthetic implants [17]. The next step in developing polymer–polymer prosthetic implants is the wear test of parts made using additive production technologies from UHWMPE and PEEK composites [18]. This test is conducted in various operating modes (loads, speeds, and environments) and intended for formulating concrete practical guidelines.

CONCLUSIONS

The methodological approach to creating bionically coherent polymer–polymer prosthetic joints on the basis of thermoplastics, such as ultrahigh molecular-weight polyethylene and high-strength polyether ether ketone, has been developed. This method is based on analyzing tribomechanical characteristics of these materials in various operating conditions (boundary lubrication and dry friction at a lack of synovial fluid in the joint). The data of system-scale tribological tests of model tribological couplings have helped substantiate the selection of fillers for UHWMPE and PEEL for the subsequent 3D printing of prosthetic implant parts.

The analysis of various carbon fillers for PEEK (40 μm KCF, graphite, $CCF_{2\,mm}$, CNT) shows that the materials recommended for creating a polymer–polymer prosthetic joint with an UHWMPE cap are PEEK/30CF and PEEK/2.5CNT. CNTs are more efficient counterbody fillers for reducing the temperature. Our further research will be aimed at studying the wear of components of polymer–polymer prosthetic implant parts made using additive production technologies [19], which is needed to formulate specific practical guidelines for using UHWMPE–PEEK tribological pairs in various operating conditions (lubrication and dry friction with a lack of synovial fluid in the joint).

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