TRIBOLOGICAL PROPERTIES OF CARBON-CARBON COMPOSITE AND OF A SURFACE LAYER OF PYROLYTIC CARBON

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The coefficient of friction and wear resistance of 2D carbon–carbon composite and of a surface layer of pyrolytic carbon were determined. To explain these results, we also measured the surface roughness and microhardness of both the composite and the layer. This material system is often used in biomedical applications (bone and joint implants), machinery sliding parts of bearings and in the aircraft industry (parts of the braking system). We studied the samples both with native ("as prepared") surfaces and also with surfaces prepared by grinding and polishing, to obtain samples with various roughness. The lowest friction coefficient was found for polished composite surface. On the other hand, the cover of pyrolitic carbon on composite improved the wear resistance. The measurements demonstrate good tribological properties of the surfaces suitable for many applications.

INTRODUCTION

Carbon–carbon composites (or C–C composites) are relatively new and promising materials with many applications. They are manufactured from carbon fibres with high strength and a high elastic modulus, and from different matrix precursors. Excellent applications of this material have appeared in the aircraft industry, in space research, in machinery for bearing planes and electrical sliding contacts [1]. The material is also promising for biomedical applications, e.g., hard tissue (bone and joint) implants, splints, screws and similar tools in orthopaedy and dental surgery. Carbon materials are generally well tolerated by living cells, so biomaterials of this type have come into routine use for constructing medical implants. The mechanical properties of C–C composites are derived from the mechanical properties of graphite in *a-b* plane.

The atoms in the second allotropic modification of carbon - graphite - create a hexagonal lattice with aliphatic hexagons of atoms connected by strong covalent bonds in the *a-b* planes. In the c direction there are only very weak physical bonds between the *a-b* planes. This causes graphite to be relatively soft, and it can act as a lubrication agent. Graphite is an electrically conductive material, its chemical resistance is much lower than that of diamond; the mechanical properties are highly anisotropic - e.g., in the a, b directions the strength and Young´s moduls is high, while in the c direction the strength is relatively low.

The mechanical properties of C–C composites are due mainly to the mechanical properties of the fibres. Carbon fibres have a very high ultimate tensile strength (about 2000-5600 MPa, according to fibre type and producer), and a high Young's modulus (about 200-700 GPa, again according to fibre type and producer) [2]. The matrix of C–C composite is formed by high-temperature pyrolysis of resins, often of phenol-formaldehyde or carbon pitch from coal or petrol. After pyrolysis, the matrix has an amorphous structure, which can be rebuilt after graphitisation to a crystalline structure, but only in the case of certain types of matrix [3]. Also, the mechanical properties of composites are connected with their architecture, i.e., with the characteristic length and distribution of fibres in the composite. In composites with long fibres, we can utilise a 1D, 2D, and multi-dimensional fibre composition (make-up). In addition, laminated structures can be constructed.

Because the surface of the composite is often coarse, and contains a large number of surface voids, it is necessary for some applications to cover it with a suitable layer. For example, a possible material for the surface layer is pyrolytic carbon (PyC), a less or more crystalline form of graphite. In the form of a surface layer, this makes pyrolytic carbon an attractive material in biomedicine [4,5,6] for coating implants, e.g., in orthopaedic and dental surgery. Pyrolytic carbon forms as result of pyrolysis, a chemical process where the bonds among the atoms of hydrocarbon molecules are broken due to high temperature and carbon is deposited on the substrate. A gaseous methane or higher hydro-

carbons at low pressure are usually used. The process temperature is about 1200-1300°C for amorphous low temperature pyrolytic carbon (LTI, low temperature isotropic), up to 2200°C for partially crystalline pyrolytic carbon, and over 2200 C for pyrolytic graphite (recomendation of IUPAC,1995).

Tribological examinations determine the friction coefficient for a combination of two materials classified as the substrate (e.g., in the form of disc) and body with specific properties and dimensions ("pin, corpuscle, ball, roller"), in a given environment. The action is usually realized by the movement of a ball or a roller of one material on the plane plate of another studied material. In the pin-on-disc analyses (ball on a plane plate) the corpuscle in the form of a roller or a non-rotating ball is placed on a surface of the specimens with the shape of a flat disc. The "pin" is loaded in advance by a defined force at a defined distance from the centre of the sample. At friction, the tangential force is caused by shear strength due to the asperities and their microhardness, which appears at the contact areas of two bodies. The axial tension loaded on the corpuscle arise the plastic deformation of both surfaces. In both cases of friction (adhesive and abrasive) the elimination of hills and transfer of material will depend on the ratio of tangential and axial stress tensions. In the case of dry friction, the test results usually depend on the following parameters: loading power, size of the contiguous surface, speed, temperature of the couple, environmental atmosphere, and, last but not least, the mechanical and physical properties of the materials of the sample and the corpuscle [7], mainly on the state and quality of their surfaces.

The values of the friction coefficient and the size of the abrasion volume are clearly connected with the roughness of the contiguous surface. Accordingly, it is necessary to observe the individual surface roughness and surface state characteristics of the samples, from the point of view of appearance and frequency of failures, including breaches. It has been demonstrated [8] that the value of the friction coefficient, and its course, i.e., the change during the examination or in running, and the wear and abrasion modes of the cutting marks depend on surface roughness. When the surface roughness is high, then intensive corpuscle jumping or "skipping" appears and, as a result, there is an extensive scatter of the measured friction coefficient values. The salient unevenness is gradually plastically deformed, and in this way the scattering of the measured values should decrease.

Unfortunately, there is very little available information on the tribological properties of pyrolytic carbon. Around 1995, LTI pyrolytic carbon was intensively studied as a material for leaflets of heart valves from the point of view of wear [9,10]. The tribological properties of some other types of carbon compounds, mainly in the form of thin films, were also studied. Most of the available information is about carbon in the form of graphite for applications in electroindustry. In [11], the pin-on-disc measurements coefficient of friction was 0.02-0.1 for a graphite pin/polycrystalline electrographite couple, at load 4N and sliding speed 0.03-0.05 m/s. It is supposed that abrasive wear creates the dangling bonds, located on the edge sites that lead to bad friction properties. Water vapour and oxygen passivate these bonds. Argon or helium decreases the friction coefficient much more, because their atoms insert themselves between the hexagonal planes of the graphite crystallites and separate them by intercalation. The cleavage strain exceeds the bonding strength between the layers, and the material can exhibit good friction properties. According to [12], the high orientation of surface crystallites obtained in the presence of water vapour during sliding leads to a pronounced decrease in the friction coefficient, and also in the wear rate.

The tribological properties of pyrolytic carbon were also studied in our laboratory [13]. In this work, the friction coefficient and wear of polished C–C composite and of PyC on both unpolished and polished C–C composite were measured using a rotating cylinder on plate (HEF tribometer, France). The coefficient of friction depends strongly on the load between 40 and 250 N. For polished samples with medium starting roughness a plateau was observed at approximately 40-100 N. This non-monotonic growth of the friction coefficient was assumed to be due to optimal conditions of graphite debris spreading on the surface of the sample. The highest friction coefficient appeared for the sample with the lowest roughness. In the case of polished C–C composite, no stable state (plateau) appeared.

Hardness is one of the basic parameters characterizing the mechanical properties of a material and also its friction and wear properties. It is known, that the volume of the worn down material (debris) is proportional not only to the load and the length of shear path, but also it should be inversely proportional to the hardness of the worn down material [14,15]. The influence of roughness on friction and wear for a diamond film/sapphire couple was studied in [16]. The friction and wear properties of thin films of polycrystalline diamond depend on both the counterface material and the properties of the diamond layer. The roughness of the diamond is critical, because it controls the amount of abrasive damage to the counterface. Also the tribological properties of other carbon compounds mainly DLC (diamond like carbon) were studied [6].

The purpose of our work was to define the tribological properties of C–C composites and their change due to the layer of pyrolitic carbon and, moreover, to find the influnce of mechanical grinding of surface on friction and wear.

EXPERIMENTAL

Specimens of 2D C–C composites were manufactured at the Institute of Rock Structure and Mechanics of AS CR (Prague, Czech Republic), by heat treatment (carbonisation) of "green" composites produced by moulding carbon fabric layers soaked with an ethanol solution of Umaform-LE phenolformaldehyde resin. A plain weave fabric made of Torayca T800 fibres was employed as reinforcement.

The square mouldings (120×120 mm) consisted of several (usually 8) layers, according to the required specimen thickness. Curing at 125°C took place in a heated mould under uni-axial pressure of 1 MPa. For tribological measurements, the cured plates were cut using a diamond saw into samples of 13.0×13.0 mm and carbonised at 1000°C in nitrogen, which converted the cured polymer matrix to a carbon material similar to glass-like carbon. The C–C composites produced in this way revealed remarkable open porosity (about 20-25 % as measured by water penetration) because certain shrinkage and mass loss (up to 30 %) took place during pyrolysis. The specimens were therefore twice impregnated with the resin and re-carbonised, which reduced the open porosity to ≈15 %. All specimens were ultimately graphitised, i.e., heat treated in argon at 2200°C [3].

The pyrolytic carbon layers were prepared by decomposition of butane in a vacuum at a pressure of 4 Pa and a temperature of 1900°C, for 300-400 minutes. The layer thickness was between 0.25-0.7 mm. For some types of samples the composite surface was ground by metallographical paper till 4000 grade. This process also enables subsequent grinding and polishing of the pyrolytic carbon layer, which was not performed in the present study. Light microscopy showed the columnar growth of the layer; and imperfections approximately parallel with the layer surface can also be seen [3]. X-ray diffraction provides a better crystallographic quality of the pyrolytic carbon layer than of the C–C composite (narrower peak 002 and 004), although different from the X-ray pattern of real graphite.

The mechanical properties of pyrolytic carbon were measured many times, but unfortunately the values are very widely spread due to the different conditions of preparation. The diversity of, for example, Young's modulus values is due not only to the heat treatment temperature, but also to type of precursor, pressure of gas etc. Most information on the mechanical properties of hard films is obtained by micro- or nanoindentation techniques. Apart from the hardness, which will be mentioned below, the modulus of elasticity value is also measured by nanoindentation technique. The referred value was $E = 7.5$ GPa for pyrolytic graphite and $E = 2.26\text{-}10.7$ GPa for isotropic carbon [6,7].

In this way, four sets of samples were prepared, with various states of the surface, which are summarized in Table 1. SET I and SET II come under C–C (composite) samples, while SET III and SET IV come under PyC/C–C samples.

Table 1. Basic definition of the samples sets.

SET I (C–C)	The samples were without surface treatment, and the surface state is given by the preparation technology for the composite.
SET II (C–C)	The surface of the composite was ground by metallographic paper (Waterproof Silicon Carbide Paper), sequentially by grade 500, 800, 1000, 4000, speed 150 rpm.
SET III (PyC/C–C)	Samples without surface treatment were covered by a layer of pyrolytic carbon about 0.6 mm in thickness.
SET IV (PyC/C–C)	Samples ground by metallographic paper (finally 4000 grade) were covered by a layer of pyrolytic carbon about 0.6 mm in thickness.

Basically, we measured the coefficient of friction and the wear during the tribometric test. The measurement of the friction coefficient was carried out directly, using a standard pin-on-disc tribometer, CSEM Instruments, Switzerland. Schematically, the diagram of our measurement system is in Figure 1. (abrasion ball on a plane plate). Next, the wear was evaluated from the shape of the spherical corpuscle ("pin") path (cutting marks) on the sample. The cross-section of the cutting marks on the sample surface is defined using standards [17-19].
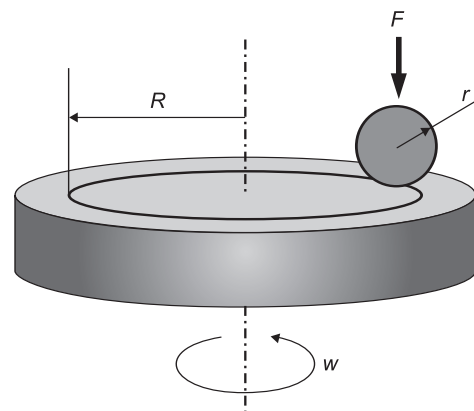

Figure 1. Diagram of an abrasion ball on a plane plate.

Here, the area of the path cross-section is defined as:

$$S_0 = [r^2 \cdot \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{1/2}] \quad (\text{mm}^2) \quad (1)$$

where d is wear track width, r is ball radius.

Full volume of sphere path is given as:

$$V_0 = 2\pi R[r^2 \cdot \sin^{-1}(d/2r) - (d/4)(4r^2 - d^2)^{1/2}] \quad (mm^3) \quad (2)$$

where R is wear track radius.

The wear volume normalised for full path and working force (specific wear) can be written as:

$$w_2 = \frac{V_0}{l \cdot F} \quad (mm^3/Nm) \quad (3)$$

l being the full path of sphere [m], F applied force [N].

During the wear test, we used a constant load of 15 N, the rotation rate was 150 rpm, the radius of the path was 2 mm, the velocity of sliding was 0.04 m/s, and the test was stopped after 4000 revolutions. The path radius r and the number of revolutions n define the full path and the time needed for the test. In this way, the full path of the pin on the sample was about 38 m. ČSN 19436 tool steel (ISO 41 9436) with hardness 62 HRC and surface roughness with $R_a = 0.01$-0.013 μm was used for the spherical pin, the diameter of the pin being 6 mm.

The full test schedule was as follows:
1. ultrasonic cleaning;
2. measurement of the sample roughness by profilometer (TALYSURF 6, Taylor-Hobson Ltd., U.K.);
3. tribometric test;
4. ultrasonic cleaning;
5. measurement of path profiles, using the TALYSURF 6 profilometer. Measurement proceeded parallel with the composite fibres, and the shape of the surface was graphically written in a suitable and known scale. In this profile we estimated the start and end of the profile of the cutting mark of the pin path. Then its width and depth were manually measured.
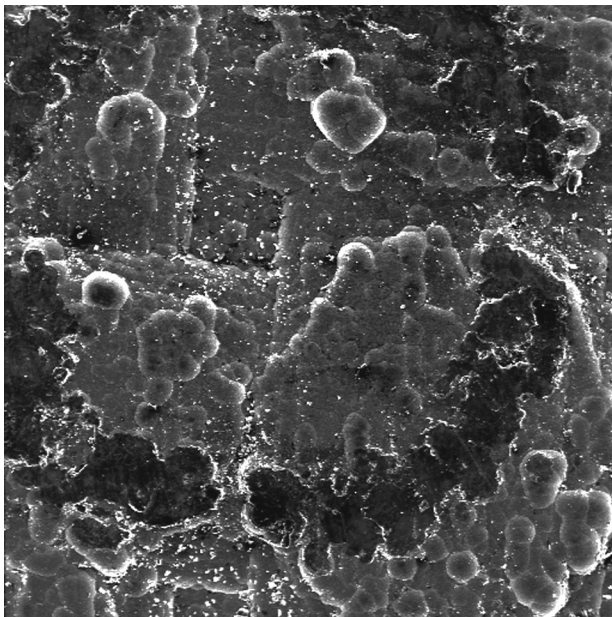6. test of microhardness.

After the test, the surface of the samples and of the spherical pin were observed in SEM (Figure 2). Also, the Vickers microhardness was measured using the microhardness tester (SHIMADZU, Japan, HMV - 2). Examples of the measurement output records are shown in Figure 3.

RESULTS

The experimental results of the roughness measurements are given in Table 2. Parameters R_a (mean roughness), R_{tm} (maximum roughness value), R_q (root mean square - parameter corresponding to R_a) and S (mean spacing of the measured adjacent local peaks) are presented in Table 2. Tables 3 and 4 summarize the results of measurements of the friction coefficient and of the wear of C–C and PyC/C–C samples, respectively.
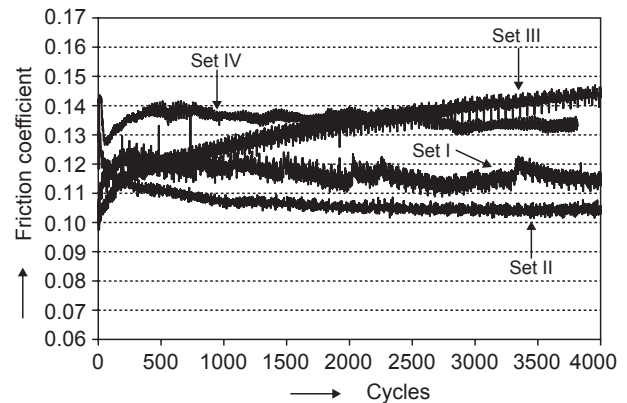

Figure 2. Detail cutting mark of the pin path.

Figure 3. Time dependence of the average values of the friction coefficient from three measurements for each set of samples.

Table 2. Initial values of the roughness parameters; average values of three measurement.

SET No.	R_a (μm)	Standard deviation	R_{tm} (μm)	Standard deviation	R_q (μm)	Standard deviation	S (μm)	Standard deviation
I	7.17	0.28	38.00	2.16	9.77	0.16	49	13
II	5.40	0.86	29.00	4.08	8.57	0.51	180	65
III	8.03	0.41	37.33	2.86	10.93	0.86	70	32
IV	3.10	0.32	19.33	2.35	5.23	0.66	81	22

We characterised the friction coefficient μ by 1) the mean value in the test, 2) the value after 250 revolutions of the disc, and 3) the final value at the end of the test. All these values were automatically recorded by the tribometer. The wear was characterised by the cross-section of the wear path S_0 (1), wear volume V_0 (2), and specific wear w_2 in units (mm³/Nm) (3).

Figures 4 and 5 show the load-depth dependencies when measuring microhardness (load 106 mN). The dashed line is the supposed dependence of elastic deformation at deloading, used for calculating of the elastic modulus. The microhardness was measured only for two sets of samples, SET II and SET IV, respectively, due to the problems in the case of rough surfaces of the unground samples. For the samples of SET II, the measurement was carried out at protruding fibres, hardness of matrix was not measured. The load-depth dependencies show very different behaviour of the two materials. Table 5 gives the average values of three microhardness measurements of samples of SET II and IV. Two values of hardness are calculated from the measurements using the evaluation value, firstly the so-called dynamical hardness, measured using a loaded indentor, i.e., connecting the elastic and plastic deformation together, and corrected hardness, measured after unloading, i.e., including only plastic deformation. This corrected hardness is obtained at the standard hardness measurement.

Table 3. Friction coefficient μ of C–C and PyC/C–C samples; average values of three measurements.

SET No.	μ					
	Mean in the test	Standard deviation	After 250 rotations	Standard deviation	Maximum in the test	Standard deviation
I	0.116	0.006	0.123	0.010	0.113	0.008
II	0.106	0.013	0.111	0.004	0.106	0.016
III	0.134	0.009	0.132	0.014	0.146	0.006
IV	0.132	0.010	0.113	0.008	0.131	0.011

Table 4. Measured wear values; average values of three measurements.

SET No.	Cross-section of wear path S_0 (10^{-2} mm²)	Standard deviation (10^{-2} mm²)	Wear volume V_0 (10^{-2} mm³)	Standard deviation (10^{-2} mm²)	Specific wear w_2 (mm³/Nm)	Standard deviation
I	0.64	0.04	5.05	0.26	107.3E-09	5.77E-09
II	0.69	0.15	5.47	0.52	116.5E-09	2.18E-09
III	0.46	0.09	3.67	0.75	78.0E-09	7.96E-09
IV	0.45	0.15	3.58	0.91	72.5E-09	8.76E-09

Table 5. Average values of selected hardness parameters of three measurements for samples of SETS II and IV.

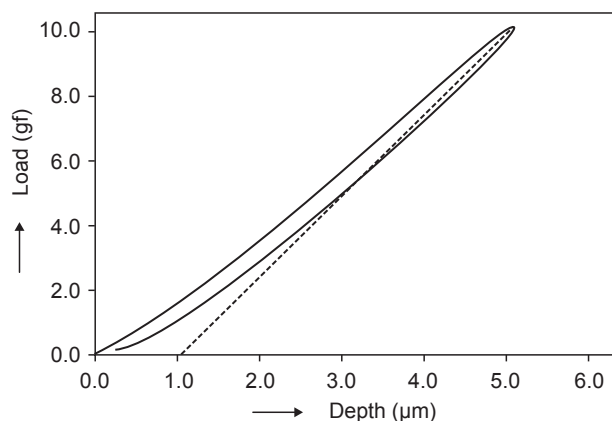| SET No.	Load (mN)	Elastic depth (μm)	Plastic depth (μm)	Maximum depth (μm)	Dynamical hardness (μm)	Corrected Hardness (MPa)	Young's Modulus (μm)
II	106	2.72	2.29	5.02	154	798	2.324
IV	106	1.05	1.49	2.55	586	1687	7.91

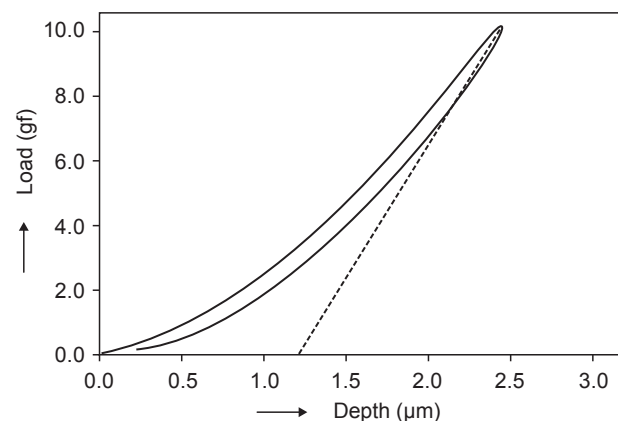Figure 4. Load-depth dependence when measuring microhardness (SET II, load 106 mN).

Figure 5. Load-depth dependence when measuring microhardness (SET IV, load 106 mN).

DISCUSSION

When measuring the time dependence of the friction coefficient, we must decide what is the importance of the sequential values and what values are the most characteristic for various samples. The average values of the friction coefficient are important, even though they do not characterize the time changes of the friction coefficient fully. We suppose that the most important friction coefficient value is the value after 250 turns. This value is taken after running-in, i.e., after grinding out most of the nodes and protrusions, and reaching some stable state. Thus, this value of friction coefficient is discussed in the following text. The lowest value of the friction coefficient is for the ground C–C composite, and the value is almost the same for unground C–C composite with a PyC layer. The differences between these values show that for the C–C composite a decrease in roughness decreases the friction coefficient by about 10 %, while in the case of the PyC layer a decrease in roughness increases the friction coefficient by about 30 %. The latter comparison is statistically significant, while the significance of the former is relatively low; the statistical significance was checked using the standard formula for Student test at significance level $\alpha = 0.05$ [20].

The data for friction and wear of PyC are very rare in literature. Our results agree generally with values for various DLC films in [21, 22]. In [21] amorphous hydrogenated carbon films were prepared using 5% C_2H_2, 95% H_2. The hardness and roughness of those films was not given. Under vacuum conditions, the value of friction coefficient was 0.12 at the start of test which agree with our results (in air). After hundred turns it decreases to about 0.08 due to roughness effect. Again it agrees with our results (sets I, II, IV), even though the decrease of friction coefficient in our measurement was slightly lower (in average for about 0.01). The same shape of time dependence of friction as for our measurement (set III) was found in [2] for fretting wear. Fretting wear occurs when two contacting materials undergo a relative oscillating displacement (stroke 0.1 to 200 μm), as can be the case for machine parts. At the RF plasma-produced DLC coating (roughness R_a 0.17 μm, E-modulus (58 ± 5) GPa and hardness 5 ± 1 GPa, with counterpart created by a polished corundum ball of 10 mm diameter), the wear rate was 1.6×10^{-7} mm³/Nm, which is comparable with our results. The increasing of fric-tion coefficient at set III is similar to a behaviour which given in [21], but the reason is unclear till now.

The differences in the friction coefficient between the C–C and PyC surfaces are low for higher roughness and much more pronounced for lower roughness. This finding signalises the possibility of an increasing dependence of friction coefficient on material type in the case of a flatter surface, perhaps due to better contact between pin and surface materials when there is lower roughness. At higher roughness, the contact between the two materials during mutual movement is much interrupted by "skipping" of the pin on the surface asperities.

As usual, the movement of the pin on a more or less rough surface causes slight instabilities of the friction coefficient, and this appears as measurement noise. The general time dependence of μ shows that for sets I, III and IV after a rapid increase the values stabilised (I and IV) or increased slowly (III). Only set II shows a steadily decreasing tendency. We suppose that these changes can be explained by greater grinding of the relatively smoother surface layer by the pin for set II than for set I, and by lubrication of the surface by carbon particles. In the case of set I, the particles stay among the surface protrusions and do not lubricate the area between pin and surface. Figure 3 also shows that, after the running-in period, the time dependence of μ is very similar for set I and set II. A similar explanation cannot be used for comparing set III and set IV, because their time dependencies are qualitatively different. We suppose that due to the higher hardness and the lower wear of PyC in comparison with C–C composites the lubrication for sets III and IV is lower. The relatively high roughness of the unground samples may change during the test, while the flatter surface changes only very little. It is also known that the friction coefficient of carbon materials depends on atmospheric humidity. Since the atmosphere was neither controlled nor checked in our tests, some differences of friction coefficient among the samples may have been due to different humidity in the tests. Even though we did not measure it, the temperature and atmospheric pressure during the tests were approximately identical, and we suppose that this influence was minimal in our test.

While measuring, we were not able to measure the wear by sample weighing because, in contrast to our primary assumptions, the wear was very low and the obtained values were within the error level. Also, we had planned to use a glass or hard plastic sphere as the pin, but these materials were too soft to make a measurable path on both the C–C composite and the pyrolytic graphite. We therefore used the above-described experimental method. The best wear resistance was found for the samples of sets III and IV, i.e., for samples covered by PyC. This is mainly due to its high hardness, which is about twice higher than the hardness of the C–C composite. For both groups of samples (I and II, III and IV), there was almost no dependence of wear resistance on surface roughness. The differences in the groups (i.e., between sets) were statistically insignificant. The calculation of the statistical agreement shows that the aver-

age values of parameter V_0 of single sets for both groups of C–C composite and C–C/PyC are statistically significantly different on significance level $\alpha = 0.05$, respectively, and the differences between unground and ground groups are not statistically significant. In any case, for applications of C–C composites in this field, a covering layer is strongly recommended, at best on a ground C–C composite surface, where the friction coefficient is stable.

An examination of the microhardness of the samples in SET II (C–C/PyC) was performed only on the fibres of composite. This hardness value gives only the partial view of the hardness of the material; unfortunately the hardness of the matrix can be hardly properly measured due to the number of imperfections (scratches and pores) in it. In spite of [6], we have found the defined hardness at the place of protruding fibres, but unfortunately, the more exact definition of the measurement place is not possible. Thus, the hardness value defines only the general state of this material phase. The hardness for PyC correspond with the hardness of pyrolitic graphite in [21]. Here, the samples were prepared at 1350°C and were examined metallographically, elastic modulus and hardness measurements were made using a nanoindentor, and densities were determined using a sinkfloat method. The metallographic analysis revealed the presence of two different types of material, the first being smooth and homogeneous, and the other having a rough and porous appearance. The hardness of the homogeneous PyC is scattered around 3.6 ±0.2 GPa, while the hardness of the rough PyC is distributed around 0.9 ±0.2 GPa. Our material shows the intermediate hardness value 1.7 GPa, which indicates lower hardness of high temperature PyC compared to low temperature homogeneous PyC in, but better then highly porous PyC prepared at the same temperature, but at different place of reactor (far from the central axis and far from the gas inlet).

CONCLUSIONS

We have determined the friction coefficient of a steel ball on an unground and a ground C-C composite, both without and with a surface layer of pyrolytic carbon. In addition, the wear resistance of these materials surfaces was studied. To explain the results, we have also measured the roughness and microhardness of these systems, with successive observation of the surface changes, using a scanning electron microscope. We found:

- the lowest friction coefficient was observed in the ground samples without a PyC layer (SET II);
- the highest friction coefficient was observed in the unground samples with a PyC layer (SET III);

- the best wear resistance was observed in the samples covered by PyC layers, almost independently of the grinding of the substrate under the layer (SETS III and IV);
- the lowest wear resistance was observed in the ground samples without a PyC layer (SETS I and II).

In the future, we consider that a harder material than tool steel should be tested as the ma-terial of the spherical pin (ideally ceramics - Al_2O_3, Si_3N_4, etc.). A larger range of loads should also be used for the friction and wear test. Unfortunately, in this case a different device will have to be used. For examinations of the microhardness of the C–C composite it would be interesting to use higher loads. In our measurements, the loads were too low to enable a better characterisation of the materials.

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TRIBOLOGICKÉ VLASTNOSTI KOMPOZITU UHLÍK–UHLÍK A JEHO POVLAKU Z PYROLYTICKÉHO UHLÍKU

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Cílem studie bylo nalézt a porovnat tribologické vlastnosti 2D kompozitu uhlík–uhlík a jeho povlakové vrstvy z pyrolytického uhlíku. Měření tribologických vlastností bylo doplněno měřením drsnosti povrchu a mikrotvrdosti tohoto kompozitního materiálu i povlaku. Zkoušený materiál byl vybrán pro jeho vlastnosti využitelné v biomedicíně (kostní a kloubní náhrady), strojírenství (kluzné části ložisek) nebo letectví (části brzdného systému). Vzorky byly před zkouškou upraveny broušením, různé parametry nerovnosti povrchu byly předmětem pro jednotlivá tribologická měření. Výsledky řešení studie potvrdily předpoklady dobrých mechanických vlastností kompozitního materiálu C–C.