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Carbon Friction Pair in Total Hip Replacement

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Abstract

The article examines the advantages of a new pair of friction of the hip joint endoprosthesis made of pyrolytic carbon. The physico-mechanical and tribological characteristics of the material and their comparison with other materials used in the friction pair of hip joint endoprostheses are presented. Information is presented about the making of a material and its strength characteristics and the results of mathematical modeling of a friction pair. The results of a comparative research of the durability between a carbon pair of friction and a ceramic pair of friction.

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1. Introduction

The need for endoprosthetics of the hip joint is constantly increasing and amounts to 1 endoprosthetics per 1000 persons [1, 2]. This reduces the age of patients undergoing arthroplasty. Consequently, the requirement for the service life of endoprostheses is growing, which averages 15 years [3, 4, 12].

When comparing the volumetric wear of friction pairs, such as metal-metal, metal-polyethylene, ceramic-ceramic, ceramic-polyethylene, the lowest wear index is for a ceramic friction couple [5–7]. A pair of metal / polyethylene friction demonstrates wear of 0,2-0,5 mm / year, friction pair ceramic / polyethylene – wear of 0,1 mm / year, metal / metal friction pair – wear of 0,002 mm / year, friction pair ceramics / ceramics – wear of 0,001 mm / year [7–11].

To increase the service life of hip joint endoprostheses, a new material is required that will exceed the available materials according to physic-mechanical and tribological properties.

2. Goal

Experimental substantiation of the advantages of a friction pair made of isotropic pyrolytic carbon (pyrocarbon).

3. Objectives

- Study the mechanical characteristics of the proposed material.
- Experimentally compare the volumetric wear of friction pairs made of pyrocarbon and ceramics.

4. Materials and methods

The basis was a carbon-containing material LTI (Low Temperature Isotropic Form Pyrolitic Carbon), containing 10% silicon (Si). LTI is used only as a coating 250 µm thick on a graphite substrate of a certain configuration.

The material of carbon steel differs made of LTI in its content of 10-20% boron (B). In order to increase the hardness and wear resistance of the material, the following composition was developed: boron 1-19%, silicon 1-9%, boron + silicon not more than 20%, isotropic pyrocarbon - the rest.

All materials containing boron in the range of 10-20% or silicon 10% satisfy the required physic-mechanical characteristics and toxicological safety.

Thus, it became possible to use the material for making monolithic structures and to further implement it in hip joint endoprostheses.

A friction pair was made of the proposed material which consisted of the following components:

- The endoprosthesis head made of pyrocarbon with titanium sleeve (Fig. 1);
- The liner with carbon insert (Fig. 2).

To determine the safety margin of the mobility unit made of pyrolytic carbon, mathematical modeling was used, which was carried out in the "ANSYS 5.7" environment.

Mathematical modeling was carried out at a load of 2250 H.

The first principal stresses (S1) characterized the tensile stress. The maximum value of the tensile stress was localized in the collar of the head sleeve and was estimated at 85,3 MPa, which is 9-10 times less than the minimum tensile strength of the titanium alloy.

Figure 1: Appearance of the endoprosthesis head.

Figure 2: Appearance of liner with carbon inserts.

The maximum value of the compression voltage was localized in the sleeve of the head and was estimated at 131 MPa, which is 6 times less than the minimum tensile strength of the titanium alloy.

Based on the results of the mathematical modeling, data on the voltage value and the safety margin of pyrolytic carbon were obtained. The average tensile stress was 40,7 MPa, and the compressive stress was 79,6 MPa, and the safety factor was 5,8 (Table 1).

To determine the maximum static load on the friction pair, a study was conducted at the specialized installation TbcTester IR5145-500 (Figure 3)

Destruction of the structure occurred at a load of 8 tons. The load angle was 45 degrees.

Table 1: Characteristics of pyrolytic carbon.

	The obtained value of voltage, MPa	The maximum stress, MPa
Maximum tensile stress (first main voltage S1)	40,7	250
The maximum compressive stress (third main voltage S3)	79,6	430

Figure 3: Installation for determining the maximum load of a friction pair.

According to GOST R 52640-2006, the torque of the hip joint endoprosthesis with carbon-carbon friction pair was determined (Fig. 4).

The magnitude of the torque and the amount of wear depend on the stresses occurring in the contact area and the size of the contact area. The probability of sample destruction depends on the strength of the materials.

The rotational speed of the bowl was set to 0,5 r/s, and for an axial load of 2250 N, a graphical torque record was made for 600 s, during which the bowl made 300 full revolutions. In order to determine the lifetime potential of the friction pair, 6 test cycles described above were performed. As a result of this test, the samples retained their integrity. The torque did not exceed 1,5 Nm, there were no free wear products on the surface of the samples, which fully complies with the requirements of GOST R 52640-2006.

The rotational speed of the bowl was set to 0,5 rpm, and with an axial load of 2250 N, a graphical torque record was made for 600 s during which the bowl made 300 full revolutions. In order to determine the lifetime potential of the friction pair, 6 test cycles described above were performed. As a result of this test, the samples retained their integrity. The torque did not exceed 1,5 Nm, there were no free wear products on the surface of the samples, which fully complies with the requirements of GOST R 52640-2006.

Figure 4: Installation for determining the torque of a pair of friction of the hip joint.

During the tests and subsequent calculation of the torque in the friction pair made of pyrolytic carbon, was 1,1 Nm. According to the requirements of GOST R 52640-2006, the torque index should not exceed 1,5 Nm. When investigating the wear rate of the proposed friction pair, data for the presence of surface wear was not obtained.

The value of the elastic modulus and the density of pyrolytic carbon are close to healthy bone tissue, which is advantageously different from other materials used (Table 2).

To determine volumetric wear, a comparative study of the pyrolytic friction pair and friction pair made of the ceramic was conducted.

The tests were carried out on the ECRB.942623.110-07.00 installation designed to test the friction pair of the hip joint endoprosthesis for volume wear (Fig. 5). The

Table 2: Physical and mechanical properties of materials.

Material	Modulus of elasticity, GPa	Density, kg / m3	Ultimate strength, MPa
Titanium	110	$4{,}5\times10^{3}$	600
Ceramics	350	$3{,}99\times10^{3}$	500
Bone	15	$2{,}4\times10^{3}$	100
Pyrocarbon	20-23	$(1{,}8\text{-}2{,}1)\times10^{3}$	450

installation was assembled in accordance with the requirements of GOST R ISO 14242-3-2013 and equipped with pressure monitoring devices, cyclic loads, cooling system and timer.

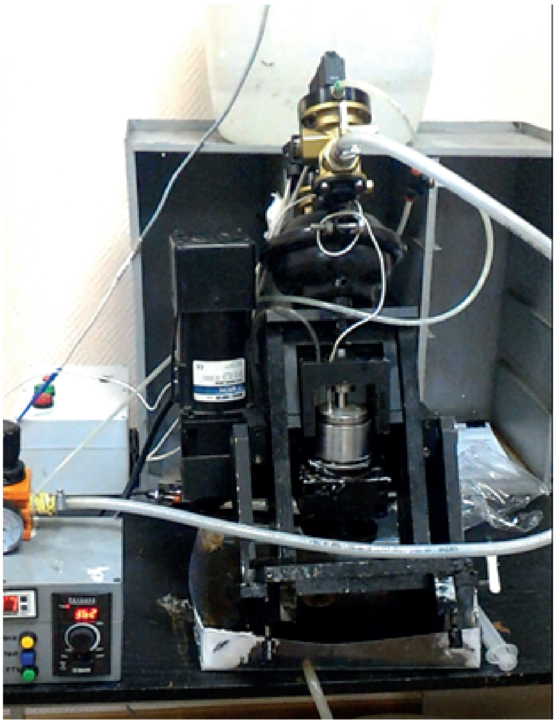

Figure 5: Installation for testing for volumetric wear of friction pairs of hip joint endoprostheses.

The reason for the termination of the test in both cases was the achievement of the number of 5000000 cycles required by GOST R ISO 14242-3-2013.

5. Test of volumetric wear of a ceramic friction pair

Test of volumetric wear of a ceramic friction pair

The test used a Zimmer ceramic head with a diameter of 28 mm and a ceramic insert of Zimmer (Fig. 6).

During the test, 5074560 cycles were passed through the test samples. According to the results of the test, the weight loss of the head was 0,009 g, the liner – 0,013 g, which corresponds to head wear by 0,0007 mm, liner by 0,001 mm in the contact surface area.

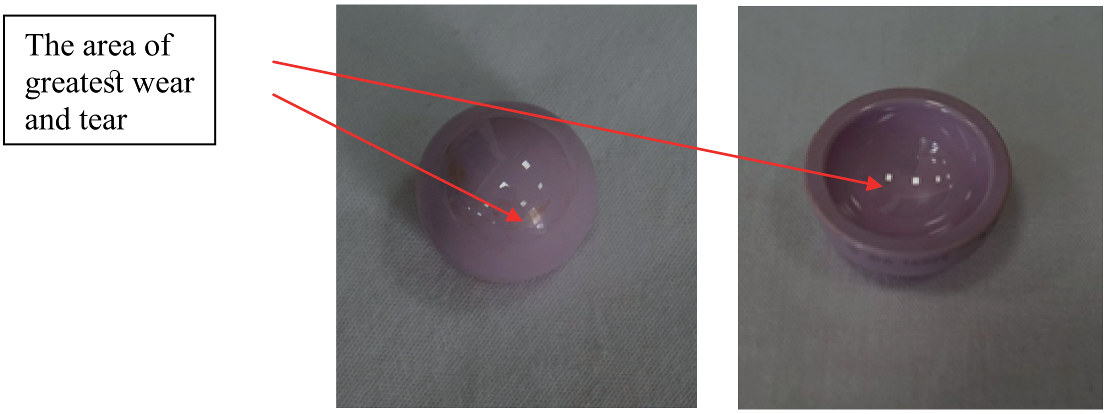

Figure 6: Ceramic friction pair after the test.

6. Test volumetric wear friction pair made of pyrocarbon

The test used a 28-mm-diameter pyrolytic carbon head and a pyrolytic carbon inserts (Figure 7).

Test samples were passed 5032800 cycles that corresponds to GOST R ISO 14242-3-2013. According to the results of the test, the weight loss of the head was 0.006 g, the liner – 0.009 g, which corresponds to the head wear at 0.00046 mm, the liner at 0.0007 mm in the contact surface area.

Figure 7: Pyrocarbon friction pair after the test.

According to World Health Organization recommendations, a person who leads an active lifestyle should take an average of 7,500 steps a day, a person will respectively perform 5 million cycles required in GOST in approximately 2 years. The calculated wear of the friction pair made of ceramics was 0.0034 mm / year, the friction pair of pyrocarbon is 0,0023 mm / year, which is 32% less than in the friction pair of ceramics (Table 3).

Table 3: Measurement results of wear of friction pairs after testing.

	Weight loss of the friction pair after the test, g	Number of cycles passed	Estimated wear of the friction pair per year
Ceramic friction pair	0,022	5074560	0,0034
Pyrocarbon friction pair	0,014	5032800	0,0023

7. Conclusions

1. Pyrocarbon friction pair has a high safety factor (450 MPa), high wear resistance (0.0034 mm / year), it withstands a high static load equal to 8 tons.

2. The friction pair of pyrolytic carbon has less volume wear than the ceramic friction pair by 32%.

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