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Comparison of the strength characteristics of a carbon friction pair of a hip joint endoprosthesis, including components from monolithic or non-monolithic pyrolytic carbon

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Abstract

Introduction The problem a large number of revision operations due to aseptic loosening after primary hip arthroplasty necessitates the search for a new material for a friction pair. The pyrocarbon, which has high tribological characteristics, can be used both in a monolithic and in a prefabricated design; however, the manufacture of a monolithic pyrocarbon block complicates production. **Aim** Compare the strength characteristics of the stem head and liner designs with monolithic and non-monolithic pyrocarbon. **Materials and methods** To assess the reliability of the designs, a digital mathematical model of the head and liner implants with a monolithic and non-monolithic pyrocarbon component was built. After the manufacture of prototypes friction pairs, an assessment of the static load on bench tests was carried out. **Results** While analyzing the mathematical model, the construct of non-monolithic pyrocarbon broke in one of the experiments, while the strength of the construct of monolithic pyrocarbon was 4.5 times higher than the stresses arising under load. While studying the maximum static load, the friction pair from monolithic pyrocarbon exceeded the maximum possible load in the human hip joint by 5 times. **Discussion** The studies allow us to be confident about the reliability of the design in in vitro studies, which will create conditions for reducing the number of revision surgeries after hip arthroplasty. **Conclusion** Based on the data obtained, the design of the head and liner of the hip joint endoprosthesis with a friction pair made of carbon material will provide high reliability under conditions of functioning in the hip joint at maximum loads. It serves as a prerequisite for conducting a clinical study of the proposed friction pair.

Keywords: hip arthroplasty, friction pair, carbon

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INTRODUCTION

The incidence of hip arthrosis is more than 10 % in patients over 35 years of age and more than 35 % in patients over 85 years of age [1]. One of the most common and effective methods of surgical treatment of coxarthrosis is total hip replacement [2, 3].

The number of hip replacements in Russia has been growing annually, from 33 thousand per year in 2008 to 76 thousand in 2019 [4]. This tendency, according to the forecasts of a number of authors, will continue in the coming decades [5, 6].

Despite the successful results of hip replacement, the problems of osteolysis and aseptic loosening of implants caused by wear particles from friction pair materials remain unresolved [7-9]. According to a number of authors, the rate of revision interventions due to aseptic loosening ranges from 3 to 39.9 % [10-12]. The main cause of aseptic loosening of endoprosthetic components is periprosthetic osteolysis, the frequency of which reaches 66 % among all the causes of aseptic loosening [13-15]. Osteolysis most often occurs due to wear particles formed during the functioning of the friction surfaces of the friction pair materials [16]. Wear particles are absorbed by macrophages what leads to the formation of a large number of cytokines that activate osteoclasts and can cause osteolysis around the endoprosthesis resulting in loosening of its components [17, 18].

The level of wear of current materials used in hip replacement reaches 0.74 mm^3/million cycles for ceramic friction pairs, 1 mm^3/million cycles for metal-to-metal friction pairs and 30-100 mm^3/million cycles of a metal-polyethylene friction pair [19-22].

It is known that high-carbon metal alloys have an initial wear level of 0.21 mm^3/million – 0.24 mm^3/million cycles, while alloys with low carbon content have a significantly higher wear rate, 0.76 mm^3/million cycles [19].

Due to the high wear resistance of carbon, it was proposed to use the carbon material applied in cardiac surgery for prosthetic heart valves which is isotropic pyrolytic carbon. However, the functioning conditions of the material in the human heart and hip joint are very different. The loads on the components of the joint endoprosthesis are much higher, and the size of the carbon component must be larger. However, it is more difficult to obtain isotropic pyrolytic carbon of the size needed to make a monolithic component than to create a prefabricated component from two parts of the material. Thus, assessing the reliability of such structures is a necessary stage of research for the manufacture of an optimal design of a friction pair for a hip joint endoprosthesis made of pyrolytic carbon.

Purpose To compare the strength characteristics of head and liner designs using monolithic and non-monolithic pyrolytic carbon.

MATERIALS AND METHODS

Two friction pair designs were studied. The head of the first design consisted of two parts of pyrolytic carbon, which were mounted on a titanium bushing; the liner was made of polyethylene and had a pyrolytic carbon insert, the diameter of the spherical surfaces was 28 mm (Fig. 1, 3).

The second design of the friction pair of the hip joint endoprosthesis consisted of a head having a monolithic pyrolytic carbon part, which was mounted on a titanium bushing. The pyrocarbon part of the liner was mounted directly into the titanium body. The diameter of the spherical surfaces was also 28 mm (Fig. 2; Fig. 4).

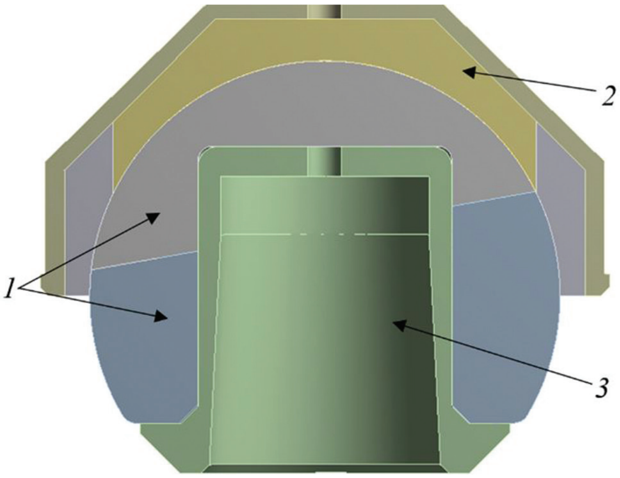

Fig. 1 The first design option for the motion unit of the hip joint endoprosthesis made of non-monolithic pyrolytic carbon: 1 – pyrolytic carbon part of the head, consisting of two parts; 2 – pyrocarbon part of the liner; 3 – titanium alloy bushing

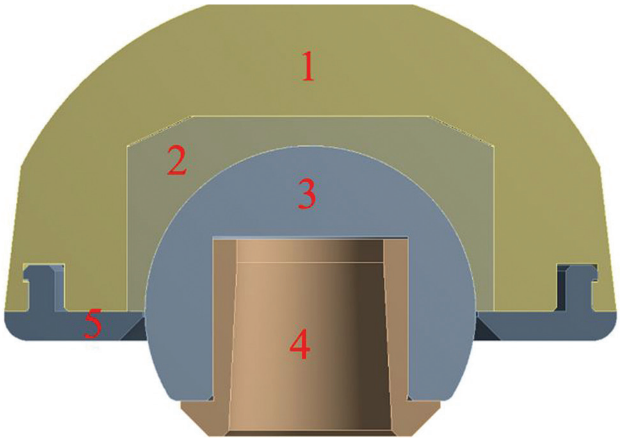

Fig. 2 The first design of the motion unit of the hip joint endoprosthesis made of pyrolytic carbon (diameter 28 mm): 1 – titanium liner; 2 – insert made of monolithic pyrocarbon; 3 – monolithic head made of pyrolytic carbon; 4 – bushing made of titanium alloy; 5 – polyethylene collar

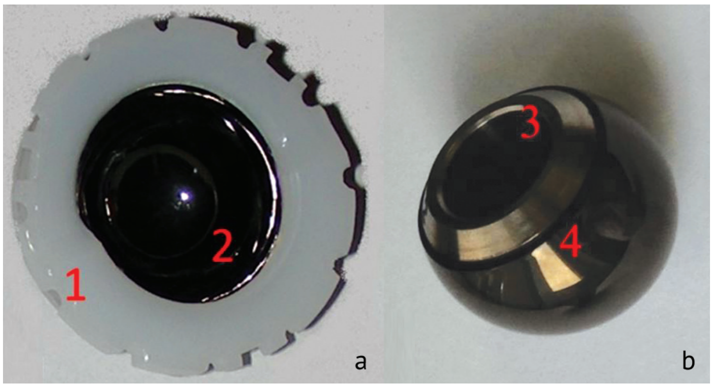

Fig. 3 Appearance of the liner (*a*) and head (*b*) with non-monolithic pyrocarbon: 1 – polyethylene liner, 2 – pyrocarbon insert, 3 – titanium bushing, 4 – pyrocarbon part of the head

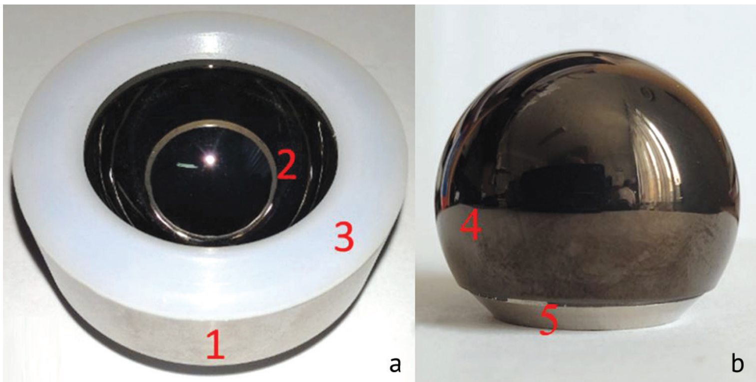

Fig. 4 Appearance of the liner (*a*) and head (*b*) with monolithic pyrocarbon: 1 – titanium body, 2 – pyrocarbon insert, 3 – polyethylene collar, 4 – pyrocarbon part of the head, 5 – titanium sleeve

The minimum gap between the block head and the liner was 0.15 mm, and the maximum gap was 0.35 mm.

The characteristics of the physical and mechanical properties of pyrolytic carbon indicate a significant difference in its resistance to fracture under tension and compression. The difference in the resistance of pyrolytic carbon to fracture during tension and compression requires consideration when assessing the strength of parts made from this material. To assess the strength of the parts of the motion unit of the hip joint endoprosthesis, the Balandin strength criterion was chosen. According to this criterion, the indicator of material destruction occurs when stress is reached in the structure of the unit.

The variable parameter was the angle of load application to the motion unit liner. Variation levels: 0° (vertical load application), 22.5° and 45°. The gap between the pyrocarbon parts of the head and the liner was 0.2 mm.

The angles of load application were selected to determine whether the stresses occurring in the structure depend on the direction of load application. The size of the gap varied within the technological tolerance of the product.

When calculating the stress-strain state of the motion unit of the hip joint endoprosthesis made of pyrolytic carbon, it is assumed that the head of the unit is fixed on the inner surface of the bushing, and the load is applied to the motion unit liner at an angle of 0° (vertical load application), 22.5° and 45°.

To conduct a study of the maximum static load on a friction pair, prototypes of the head and liner with monolithic and non-monolithic parts of pyrolytic carbon were manufactured. The design of the components corresponded to the schemes used in mathematical modeling (Fig. 3, 4).

The study was conducted on a specialized system TbcTester IR5145-500. The angle of stress application was 45°.

RESULTS

For both constructs, under all considered loading conditions, the maximum values of relative stresses arise in places of stress concentration, which are the edges or rounding on the inner surface of the head of the motion unit.

The second most important place for stress concentration is the contact patch between the spherical surfaces of the head and the liner of the motion unit.

A high level of relative stress occurs when the end surface of the titanium bushing contacts the inner surface of the head. Contact occurs when an axial load is applied and is accompanied by the occurrence of high stresses of a local nature.

When evaluating head designs with a non-monolithic pyrolytic carbon part, a peculiarity was that the load concentrations fell on the connection zones of the pyrolytic carbon parts. In one experiment, the stress exceeded the strength of the structure, which may cause the break of the structure. For a friction pair with monolithic pyrolytic carbon, the safety margin was 4.5 times higher than the stresses that arose during the modeling (Table 1).

Thus, the design of a friction pair with monolithic pyrolytic carbon provides a lower level of relative stresses in the entire considered range of angles of load application compared to the design in which non-monolithic pyrolytic carbon was used. The construct of a friction pair with non-monolithic pyrolytic carbon broke in an experiment with a load applied along the axis of the neck.

Table 1

Maximum values of relative stresses in the head and liner with monolithic and non-monolithic pyrocarbon

Construct variant	Angle of stress application		
	0°	22.5°	45°
Non-monolithic pirocarbon	1.628	0.580	0.390
Monolithic pirocarbon	0.149	0.222	0.202

According to the results of the static load study, the destruction of the friction pair with non-monolithic pyrolytic carbon was recorded at 1.5 tons. The destruction began with the deformation of the polyethylene adapter of the insert, which led to the destruction of the carbon liner.

The destruction of the friction pair with monolithic pyrocarbon occurred at a load of 3.5 tons. This value is 5 times higher than the maximum loads occurring in the hip joint.

Thus, the construct of a friction pair with monolithic pyrocarbon showed higher resistance to static loads than the design of a friction pair with non-monolithic pyrocarbon.

DISCUSSION

Advances in technology, improved materials and a better understanding of natural tissue responses will certainly lead to breakthroughs in implant selection. Due to the aging population, the number of joint replacement surgeries has increased in recent years [23]. Consequently, the number of revision surgeries is also increasing, since the life expectancy of patients is longer than that of endoprostheses [24-27].

Current trends in prosthetic design emphasize the importance of biocompatible materials that are durable enough to withstand the increasingly active lifestyles of many patients while generating minimal wear debris. Since the main problems affecting the survival of the prosthesis is wear and wear particles, extensive research has been currently carried out to improve such biomaterials and provide an "infinite life of the endoprosthesis".

Despite the currently available materials for friction pairs, such as ceramics, metals, and polyethylene [28], the use of carbon materials for friction pairs seems to us to be an extremely promising direction.

Despite the fact that the reliability of the structure after implantation has yet to be studied, we can confidently speak about the high mechanical strength of the design of the head and liner of the hip joint endoprosthesis with a friction pair made of carbon material. High tribological characteristics of materials containing carbon were described in the literature, and it is statedthat the improvement in wear resistance is directly proportional to the increase in the carbon content in the material [19].

Thus, the use of a material with the potential to multiply the surviva of the hip joint endoprosthesis will help to significantly improve the quality of life of such patients and will increase the age range for the use of this type of surgical care without the risk of early revision interventions [29, 30].

CONCLUSION

Technical result In all the experiments, only the friction pair structure with monolithic pyrolytic carbon withstood the specified loading conditions for structures in the mathematical model, with a safety margin of 4.5. The design of a friction pair with non-monolithic pyrocarbon collapsed in an experiment with a load applied along the axis of the neck. By comparing the maximum static load, the strength of the structure with monolithic pyrolytic carbon was 2.3 times higher than the strength of the structure with non-monolithic pyrolytic carbon.

Clinical relevance Due to the high strength characteristics of the friction pair construct with monolithic pyrocarbon and the insufficient strength of the structure with non-monolithic pyrocarbon, only the design with monolithic pyrocarbon might be used for clinical practice.

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Mitroshin A.N. – conceptualization; validation; writing – reviewing and editing; control; project management.
Ksenofontov M.A. – methodology; formal analysis; study; data processing; writing - the original version; visualization, writing – reviewing and editing.
Kosmynin D.A. – study; writing – the original version; data processing; visualization.