DESENVOLVIMENTO DE TECNOLOGIA DE OBTENÇÃO DE MATERIAL COMPOSITIVO NO AGLUTINANTE DE SILÍCIO ORGÂNICO PARA APLICAÇÃO EM MOTORES DE FOGUETES ELÉTRICOS ESPACIAIS

DEVELOPMENT OF TECHNOLOGIES FOR OBTAINING COMPOSITE MATERIAL BASED ON SILICONE BINDER FOR ITS FURTHER USE IN SPACE ELECTRIC ROCKET ENGINES

РАЗРАБОТКА ТЕХНОЛОГИИ ПОЛУЧЕНИЯ КОМПОЗИЦИОННОГО МАТЕРИАЛА НА КРЕМНИЙОРГАНИЧЕСКОМ СВЯЗУЮЩЕМ ДЛЯ ПРИМЕНЕНИЯ В КОСМИЧЕСКИХ ЭЛЕКТРИЧЕСКИХ РАКЕТНЫХ ДВИГАТЕЛЯХ

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RESUMO

O trabalho é dedicado à criação de um material compósito à prova de vácuo num aglutinante inorgânico para a fabricação de peças dielétricas de motores de propulsão elétrica de grande diâmetro, levando em consideração os requisitos de permeabilidade eletromagnética, resistência ao calor e resistência à vibração. Durante a pesquisa verificou-se que a maneira mais eficaz de aumentar a resistência à vibração de peças de cerâmica de paredes finas é montá-las em cola resistente ao calor elástica dos setores cerâmicos de forma simplificada. O experimento foi realizado utilizando dois protótipos funcionais de câmaras de descarga de motores de foguetes elétricos. Estabelece-se que o Protótipo A tem uma densidade maior de material em comparação com o Protótipo B. Ao mesmo tempo, as propriedades eletroquímicas e o limite mais alto da temperatura máxima do Protótipo A são melhores que os do Protótipo B.

Palavras-chave: *temperatura de trabalho, protótipo, câmara de descarga de gás, peças cerâmicas.*

ABSTRACT

This work is devoted to creation of vacuum-tight composite material based on organic binder for manufacture of dielectric parts for electric rocket engines of large diameter, considering requirements to their electromagnetic permeability, thermal stability and vibration resistance. Results of the study has showed the most effective way to increase the vibrational resistance of thin-walled ceramic parts is to assemble them on an elastic heat-resistant adhesive from ceramic sectors of simplified shape. The experiment was conducted using two functional prototypes of discharge chambers of electric rocket engine. It has been disclosed that Prototype A has a higher density of material compared to Prototype B. Moreover, the electrochemical properties and the highest temperature limit of Prototype A are better than that of Prototype B.

Keywords: *operating temperature, prototype, electrostatic discharge chamber and ceramic parts.*

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АННОТАЦИЯ

Работа посвящена созданию вакуумплотного композиционного материала на неорганическом связующем для изготовления диэлектрических деталей электроракетных двигателей большого диаметра с учетом требований к их электромагнитной проницаемости термостойкости и вибростойкости. В процессе исследования было установлено, что наиболее эффективным способом увеличить вибрационную стойкость тонкостенных керамических деталей является их сборка на эластичном термостойком клее из керамических секторов упрощенной формы. Эксперимент проводился с использованием двух функциональных прототипов разрядных камер ЭРД. Установлено, что Прототип А имеет большую плотность материала в сравнении с Прототипом В. При этом электрохимические свойства и наивысший рубеж максимальной температуры Прототипа А лучше, чем у Прототипа В.

Ключевые слова: *рабочая температура, Прототип, газоразрядная камера, керамические детали.*

INTRODUCTION

Electric rocket engines (EREs) are c have been used since 70s of the last century for stabilization and correction of geostationary satellite orbits (GSO). Mode of operation of electric motors is based on formation of working gas plasma with further acceleration of its components through electric field (Barbosa and Sismanoglu, 2017). The flow rate of the working gas is much higher compared to conventional chemical rocket engines. It is between 5 and 60 km/s for different types of electric rocket engines, which allows substantial saving of the mass of the working body while ensuring considerable operation life, which is equal to several tens of thousands of hours. Reducing the mass of the working body provides a significant increase in payload of the spacecraft (CA).

Modern space industry (Antropov *et al.*, 2002; Gorshkov *et al.*, 2008) is focused on development of electric space engines for the following purposes: correction of spacecraft orbit, raising of spacecraft to geostationary orbit and also as main propulsion system in interplanetary transfer (Formalev *et al.*, 2016; Formalev and Rabinskii, 2014).

So one of electric space engine was used as propulsion engine in the 7-year (2003-2010) mission of the Hayabusi 1 of the Japan Space Agency JAXA during the flight to the Itokawa asteroid and back, as well as the Hayabusi 2 mission of flight to the 1999 JU3 asteroid, which runs in present time It should also be noted that the longest project in the history of astronautics, i.e. the flight of Voyager 1 and Voyager 2 spacecraft to the boundaries of the solar system (NASA, USA, since 1977) became possible not least due to the use of electro-thermal hydrazine engines. Today, these engines are considered for use propulsion engines in other deep-space development missions, including flight to Mars (Gorshkov *et al.*, 2008) and other solar system objects.

Ceramic materials are widely used in critical nodes of the structures (Loeb, 2015) in electric rocket engines of two types: stationary plasma engines (SPE) (Tazetdinov *et al.*, 2002; Mikheev *et al.*, 1983) and high-frequency ion engines (HFIE) (Semenov, 2015). SPE lifetime is determined by the wear of the ceramic insulator of the gas-discharge channel, bombarded by plasma flowing out of the engine nozzle (Tazetdinov *et al.*, 2002; Sitnikov, 2017). In most promising HFIE engine, one of the major elements of the structure that maintains plasma discharge is ceramic electrostatic discharge chamber (EDC). Electrostatic discharge chamber of high-frequency ion engine is a thin-walled (4-5 mm thick) bowl, and an increase in its diameter leads to significant technological difficulties in the manufacture of the above-mentioned materials. The Russia has developed the technology for manufacturing EDC from alumina oxide ceramics and silicon nitride-based composite for engines with EDC diameter up to 160 mm (Semenov, 2015; Khartov et al., 2013; Rabinsky *et al.*, 2016). EDC from these materials have optimum performance properties, in particular, high permeability to the electromagnetic field in the megahertz frequency range, satisfactory mechanical vibration strength and high erosion resistance to ion-plasma effect of low-temperature discharge plasma (Khartov *et al.*, 2013; Yanagida, 1986; Gnesin, 1987; Pogodin *et al.*, 2016). However, the further development of HFIE technology implies an increase in their capacity, and EDC size respectively, which is significantly limited by the development of modern technologies for the production of large-sized thin-walled ceramic products. In spite of difficulty in molding and sintering such products in accordance with the canons of modern technology of ceramics (Pogodin *et al.*, 2016; Poliakov et al., 2016; Ripetsky *et al.*, 2016; Rabinsky *et al.*, 2016; Pogodin *et al.*, 2016; Lurie *et al.*, 2015; Formalev *et al.*, 2015; Lurie *et al.*, 2011; Mogilevich *et al.*, 2016), the other essential problem is the need to ensure resistance to vibration when spacecraft is injected into near-earth orbit. To solve these problems, research work is being carried out on the creation of a vacuum-tight composite material on an inorganic binder for the production of large-diameter EDCs for high-frequency ion engines , taking into account the requirements of electromagnetic permeability and vibration-resistance of the product.

MATERIALS AND METHODS

As part of the work, the researchers have established the following tasks:

1. Development of physicochemical bases for the production of composite materials with inorganic matrix and organic filler (bandage), as well as materials in organic-silicon binder to increase the vibration resistance of thin-walled items of large size.

2. Development of technology of molding and synthesis of large-sized (up to 600 mm) thin-walled (6...7 mm) products of complex geometric shape (spherical, conical thin-walled products) from ceramic systems that have high dielectric and mechanical properties (silicon nitride, silicon nitride – aluminum oxide, silicon oxide, silicon nitride – silicon oxinitride).

3. Conducting researches of electrophysical, mechanical and other operational properties of developed composite materials and products from them.

At first stage of work on development of parts and components for electric rocket engine, the project participants has developed and studied a family of composite ceramic materials based on silicon nitride. They have developed technology and prepared laboratory areas for several alternative (including additive) methods of molding blanks from of polycrystalline silicon (reinforced with inorganic fillers) such as:

• Hot molding of ceramics;

• Electrophoretic molding of ceramics;

• Binder injection method (Binder Jetting);

• Fused deposition modeling (FDM);

For the synthesis of molds, the technology of reactive sintering of silicon nitride with a reduced nitrogen pressure (up to 0.5At) and a low temperature (up to 1400C) was also developed. This technology made it possible to obtain a wide range of items made from polycrystalline silicon blanks characterized by increased resistance to ion-plasma sputtering (Figure 1). Full range of experimental studies has been carried out with subsequent processing and synthesis of obtained data for scientific substantiation of the use of this ceramic for manufacture of ERE parts. We used our own software or technological equipment (including those related to additive processes) and tested techniques for using CAD-CAM systems in designing. We also have developed effective methods of obtaining and controlling ceramic raw material, as well as the output control of the mechanical and electrophysical properties of obtained products.

RESULTS AND DISCUSSION

Further studies have shown that low technological level and resistance of finished item to vibration are insuperable difficulties upon production of monolithic ceramic parts for large sized electric rocket engines (diameter more than 300 mm, wall of the chamber is 5 ... 8 mm) even from such non-shrinkable material as silicon nitride. Experiments have shown that the most effective way to increase the vibration resistance of thin-walled ceramic parts is to assemble them on an elastic heat-resistant adhesive from ceramic sectors of a simplified shape (obtained by conventional ceramic technology (Figure 2)) or molding monolithic parts from ceramic-filled fillers of thermoresistant organic-silicone binders.

The works on production of prototypes o electrostatic discharge chambers of electric rocket engines with increased vibration resistance from glued thin-walled ceramic parts, as well as molding of chambers from organic-silicone binders filled with ceramic filler allowed the following requirements to be applied to used organic-silicone composition:

• Thermal oxidation resistance up to 4000C.

• High dielectric properties in the frequency range from 50 Hz to 10 MHz.

• High adhesion of the binder/adhesive to the used ceramic materials (corundum, quartz, silicon nitride).

• High elasticity of the binder/adhesive in the resulting chamber.

As a part experimental work, we have created two functional prototypes of electrostatic discharge chamber for electric rocket engine based on previously described technological and materials science approaches .

The first of them (Prototype A) was glued on test stand from silicon nitride plates 5 ... 6 mm thick, using organic-silicone binder. The original plates were obtained by the technology of hot casting of ceramics from polycrystalline silicon powder, followed by low-temperature reaction synthesis in the nitrogen stream. Glued surfaces were subject to sandblasting treatment. Single-component composition based on polydimethylsiloxane polymer was used as glue. Gluing process took place at room temperature in open air.

The second prototype (Prototype B) was made of a two-component silicone compound based on a polymethylphenylsiloxane polymer filled with 60% w silica monofraction powder of silicon dioxide (50% of the particles of this powder had a size of 10 – 30 μm, 90% of particles had the size of not more 40 μm). The purity of the powder was 99.9% of the SiO_2 content. The surface of the prototype was formed by hydraulic press with a pressure of up to 0.6 MPa in a steel air-tight frame fitted with air outlets. Binder was hardened in first-stage vacuum at room temperature.

Both prototypes of gas-discharge chambers of electric rocket engines were tested in accordance with GOST B 24880-81, GOST RV 20.57.305-98, GOST RV 50674-94 and GOST V 22589-86.

The integral physical properties of material of prototype A were determined mainly by the properties of silicon nitride:

• Density: 3000 kg / m3.
• Thermal conductivity: 5 ... 10 W / (mK) at 300 K
• Tensile strain at break (in adhesive seams): 40%.
• The temperature coefficient of linear expansion is 3,4,10-6 K-1
• Electrical strength: 11 – 20 kV / mm.
• Tangent of the dielectric loss angle: 6 ... 8 · 10-3.

Material of prototype B had the following properties:
• Shore hardness: 40..50 A.
• Density: 2000 kg/m3.
• Elasticity: linear elongation of about 40% of residual deformation.
• Relative elongation at break: 70%.
• Tensile strain at break – 0.2 ... 0.3 MPa.
• Shrinkage after vulcanization: 0.2 ... 0.3% by volume.
• The temperature coefficient of linear expansion: 1.0 ... 1.5 · 10-3K-1
• Electrical strength: 15 – 20 kV/ mm.
• Tangent of the dielectric loss angle: 0.2 ... 0.02.

The material of both prototypes was examined by the TGA method (thermogravimetric analysis). It was disclosed that the resistance to thermal decomposition of Prototype A adhesive is limited to a temperature of 300C. The binder of Prototype B can withstand heating up to 400C without any signs of destruction.

Results of the test of prototypes on test stand simulating the operation of electric rocket engine in open space have shown that both chambers (Prototype A and Prototype B) are able to provide acceptable operation parameters of electric rocket engine.

CONCLUSIONS:

This work has determined chemical and phase composition of the polymer-ceramic composites, which provide the required performance characteristics of the electric rocket engine, such as: radio transparency, feasibility, heat resistance and vibration resistance. We have developed two technologies for manufacturing products from composite ceramic materials and experimental elements of the technological equipment for obtaining parts of electric rocket engine from the developed polymer-ceramic composite materials. It is shown that the density of the material used in the production of Prototype B is 1.5 times lower than that of Prototype A, but its electrophysical properties and the maximum operating temperature are somewhat lower, which requires additional work to optimize the composition of the binder. At the same time, electrostatic discharge chamber of electric rocket engine, manufactured by method used in Prototype B, has higher technological level and, presumably, higher reliability.

The performed work showed that the use of polymer-ceramic composites for the manufacture of electrostatic discharge chambers of electric rocket engine allows significant increase in the dimensions, vibration-resistance and feasibility of these space items.

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Figure 1. *Electrostatic discharge chamber for electric space engine 180 mm in diameter from silicon nitride*

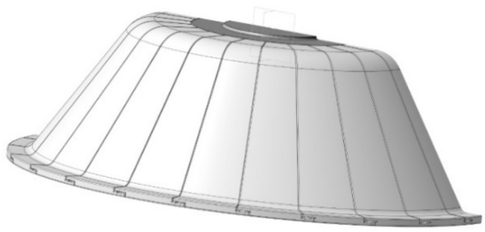

Figure 2. *Appearance of the prototype of electrostatic discharge chamber of the electric rocket engine, glued from thin-walled ceramic parts (Prototype A)*