Fabrication and testing of rocket engine construction elements by addictive production approach

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Abstract—For the first time, using the technology of selective laser sintering, prototypes of rocket engine compressor blades were manufactured with subsequent analysis of the strength, technological, physical and mechanical characteristics of the product. The physical and mechanical properties of the manufactured blades were investigated, it was found that the short-term strength limit at 20 °C is 1450 MPa, and at 300 °C the ultimate strength is 1300 MPa, thus thermal losses in deformation resistance are no more than 12%, which allows the material to be used in aircraft construction, including for supersonic aircraft.

Keywords—Addictive production, strength, composites, 3D printing.

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1. Introduction

According to the structure of the additive manufacturing market, the main directions are automotive, medicine, industry, consumer electronics, architecture, as well as aviation and aerospace due to significant investments of major aviation companies in the development of industrial applications of additive manufacturing [1],[2],[3],[4],[5],[6],[7],[8],[9],[10],[11],[12],[13],[14],[15],[16],[17],[18]. The development of modern aircraft is proceeding at a rapid pace, which places increased demands on traditional production technologies, which are becoming increasingly difficult to compete with modern ones, for example, 3D printing. This technology allows not only to build a model quickly and at low cost, but also to demonstrate the assembly and operation process. For the aviation industry, one of the main drivers of improvement is the reduction in the weight of the flying components [19],[20],[21],[22],[23],[24],[25],[26],[27],[28],[29],[30],[31],[32],[33],[34],[35]. The additive manufacturing process is capable of creating physical parts starting from a digital input. Furthermore, a wide range of composite materials based on nanocomponents described in [36],[37],[38],[39],[40],[41],[42],[43],[44],[45],[46],[47],[48],[49],[50],[51],[52],[53],[54],[55],[56],[57],[58],[59],[60] can be successfully used for addictive manufacturing process. In order to achieve the required geometry, various operating parameters, such as tool paths and projections, must be defined in the software, which depend on the material and equipment used. This is one of the biggest advantages of additive manufacturing: production of parts with little need for special tooling to determine the shape [61],[62],[63],[64],[65],[66],[67],[68],[69],[70],[71],[72],[73],[74],[75],[76],[77],[78],[79].

Low-thrust rocket engines such as electric rocket motors are widely used in space technology to stabilize and correct the orbits of geostationary satellites, and as propulsion engines for spacecraft in several interplanetary missions. The principle of operation of an electric rocket engine consists in organizing a plasma discharge of the working gas with subsequent acceleration of plasma ions using an electric field. The outflow rate of working gas ions is significantly higher than in traditional chemical rocket engines. For various types of electric rocket engines, it ranges from 5 to 60 km/s, which allows significant savings in the mass of the working fluid with a significant resource of their work, amounting to several tens of thousands of hours. A decrease in the mass of the working body makes it possible to increase the mass of the spacecraft payload. In one of the schemes of this engine - a high-frequency ion engine - the working gas plasma is formed under the influence of a high-frequency electromagnetic field inside a thin-walled bowl of a ceramic gas-discharge chamber. To increase the power of such an engine, it is necessary to increase the diameter of the gas-discharge chamber to a value of 500 mm and more while maintaining the wall thickness at the same level (no thicker than 4-5 mm). The used samples of gas-discharge chambers made of alumina ceramics and a ceramic composite based on silicon nitride with a chamber diameter of up to 160 mm, in principle, have sufficient operational properties. However, an increase in the diameter of the gas-discharge chambers above 160 mm is significantly limited by the capabilities of the technology for the production of ceramic products. In addition, along with the difficulty of forming and sintering such items, a significant operational problem of ceramic gas-discharge chambers is their low resistance to vibration loads arising during the launch of spacecraft into near-earth orbit. The solution to this problem would be to manufacture gas-discharge chambers from a composite material of the composition: ceramic particles (fibers) - organosilicon or ceramic matrix. The advantages of such composite materials are, above all, their high dielectric properties and very high vibration resistance. The matrix of such materials can be made from silicone elastomers. Finely dispersed powders of such inorganic ceramic materials as aluminum, beryllium or silicon oxides, boron or silicon nitrides, etc. can be used as a dispersed filler.

Prospects for the creation of the proposed new class of composite materials open up significant opportunities in the development of new structural materials for space technology: the creation of multifunctional composites with increased parameters of rigidity, thermal stability and damping will allow in the future to implement products with increased mass efficiency. Thus, the volume of structural materials of engines, the density of which is very high (to ensure the required strength and heat resistance), as part of the structure of spacecraft can be reduced.

The fundamental nature of the problem under consideration lies in the fact that technologies for creating such composite materials and ceramic fillers do not currently exist. For example, for the particle size of ceramic fillers (from tens of nanometers to tens of microns), the optimal calculated thickness of the polymer matrix should be from a few to hundreds of nanometers, which requires the implementation of new coating techniques, the development of new methods for dispersing the filler and curing the samples. These methods should ensure the possibility of obtaining high-quality defect-free samples of gas-discharge chambers of a given (calculated) thickness. In particular, one of the most difficult problems in the formation of ceramic products is the need to work with the original ceramic masses containing coarse (up to 100 microns and higher) grains with abrasive properties. Initial compositions for prototyping, having such particles in their granulometric composition, significantly complicate the 3D printing process due to the constant clogging of technological channels as a result of their sedimentation. Fighting channel clogging is usually accomplished by widening the flow area, which ultimately reduces print accuracy. The development of promising techniques for manufacturing products using 3D printing from a wide range of materials is, therefore, an extremely urgent task.

The next task is to develop approaches to the creation of dispersed systems synthesized in a discharge of nano- and microparticles of organic-inorganic materials in the form of particles with organosilicon polymer coatings, to study the principles of their formation and properties, including using ultrasonic cavitation, as well as the principles of 3D - printing of composite materials from ceramic nanoparticles and polymer/ceramic matrices. An important point in the technology being developed is the optimization of the process of passage of dispersions of large (up to 200 microns) ceramic particles in paraffinic technological bonds with a low content of paraffin at temperatures close to the solidification temperature of the bond through the technological channels (for example, the print head nozzle) of the installation. For this, along with precise control of the temperature of the modeling composition, it is proposed to use the effect of ultrasonic cavitation directly in narrow channels by introducing an indenter into the channel.

Since the resulting composite material has an anisotropic nature of heat transfer (thermal conductivity is described not by a scalar quantity - a coefficient, but by a tensor), for accurate modeling of temperature fields, it is necessary to accurately determine the thermophysical characteristics, including the nonlinear dependences of the components of the thermal conductivity tensor on temperature, since otherwise, computational experiments in modeling temperature fields can give significant errors.

At the final stage, experimental studies of the dynamic properties of samples of the investigated materials (components and composites) will be carried out to confirm the results of calculations and their correction (if necessary), theoretical studies and modeling of the effect of uneven coating thickness, polydisperse fractional composition and imperfection of the shape of ceramic filler particles on effective dynamic properties of the composite, determination of the optimal compositions of composites taking into account these effects. Modeling the effective damping properties of the considered composites under shock loading and optimizing the structure to obtain impact-resistant materials with effective parameters of absorption of mechanical energy, as well as modeling the thermoelastic and strength characteristics of dispersed-reinforced composites, samples of gas-discharge chambers and comparing the calculations with the experimental results.

The technological task of the work is the development and manufacture of the installation and debugging of a new technology of three-dimensional modeling and the release of experimental samples of gas-discharge chambers in order to identify the fundamental possibilities of this molding method for obtaining ceramic parts of low-thrust rocket engines. The operations of forming and sintering powders are one of the most critical operations in the technological cycle for producing ceramic products. It is at these stages of the production cycle of obtaining a ceramic product that its main mechanical properties are formed.

The task of technological preparation of additive manufacturing on an experimental installation for layer-by-layer modeling of composite ceramic samples includes the calculation of layer-by-layer representation in accordance with the geometric shape of the part, as well as from the formation of trajectories of motion of the actuators of the experimental installation to fill the internal volumes of the part workpiece being grown. The structure of the software designed to run on a personal computer should provide technological preparation for the manufacture of the product and the formation of a set of control commands in the lowest-level and universal (as far as possible) form, but without reference to the hardware features of a particular actuator.

Thus, the aim of the work was to manufacture a rocket engine compressor blade using selective laser sintering technology, to analyze the strength and technological characteristics, and to control the quality of the resulting workpiece.

2. Procedure of selective laser sintering

Before carrying out the selective laser sintering process, the electronic model of the blades was saved in the STL (Stereolithography) format, intended for storing three-dimensional models in additive technologies. The Selective Laser Melting (SLM) installation has been prepared in accordance with the instruction manual. The selective laser sintering process has already been studied by several groups of researchers [1],[2],[3],[4],[5],[6],[7],[8]. The sintering process took place automatically. The metal-powder composition was placed into the feed hopper of the SLM installation, the building plate was bolted, after which the selective laser sintering process was launched in automatic mode on the control panel of the SLM installation. The blades were obtained, shown in Fig. 1. In order to facilitate the subsequent examination, before removing the blades from the installation, the primary cleaning of the blanks in the build chamber from the metal-powder composition was carried out using a molar brush, for which the glove port on the door of the building chamber of the SLM installation was opened in accordance with the instruction manual.

Fig. 1 rd blades obtained by selective laser sintering.

The microstructure of the blades was studied using an Axiovert 40 MAT microscope at x50 magnification. The wall thickness and porosity were measured at the leading edge of the blade, which is shown in Fig. 2.

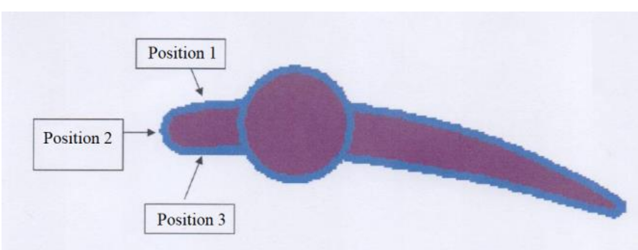

Fig. 2 cross section of the blade.

According to the measurement results, the thickness of position 1 is 0,68 ... 0,75 mm, the value of position 2 is 0,34 ... 0,37 mm, the wall thickness from the side of position 3 is 0,47 ... 0,53 mm. The structure of the blades is a melt bath in the form of segments of a circle. There is no overheating (melting) and burnout in the microstructure of the material of the blades, there are no cold and hot cracks.

3. Microscopy and X-ray control

A metallographic study of the blades was carried out. Luminescence analysis showed the presence of a powder non-fusion defect with a size of 0,085x0,043 mm. Scanning electron microscopy (SEM) studies showed the microstructure of blades with no defects (Fig. 3).

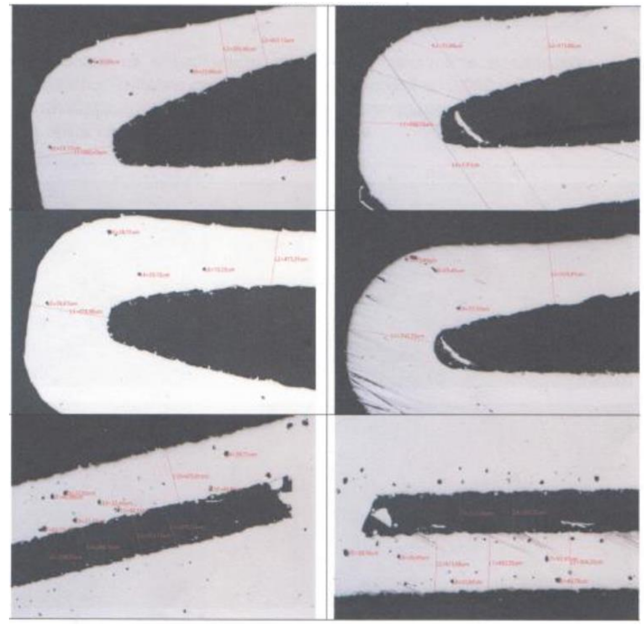

Fig. 3 results of SEM control of a rocket engine blade.

It should be noted that the surface of the blades is subjected to subsequent machining, and any metallurgical defects that can be removed by the machining are allowed.

The mechanical characteristics of the blades were determined and uniaxial tensile tests were carried out on the sample. The results obtained showed that the blades made by the selective laser sintering method have the same characteristics and quality as the blades made by the traditional method.

4. Conclusion

A pilot batch of rocket engine compressor blades was manufactured using the selective laser sintering technology (SLS). The study of the obtained blanks was carried out by the method of X-ray and luminescent non-destructive testing to ensure the quality of resulting materials. It is shown that there are no defects in the structure of the blades, and the identified defects in the surface layer of the material can be easily removed by subsequent mechanical treatment. The proposed technology opens the prospective for facilitated fabrication of high-quality blades for heavy duty rocket engines.

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