Metal-coated carbon fiber model

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Abstract. The results of the modeling of the stress-strain state of the filaments from which the carbon unidirectional tape LUP is made, are provided for the latter’s initial state and after applying a grade 12X18H10T stainless steel coating thereon. The results of calculations were compared to experimental data. Magnetron sputtering was used to apply a metallic coating, with pre-cleaning the carbon tape. These models allow to optimize the thickness and choose the type of metallic coating.

Keywords: carbon tape, filament, metal coating, modeling.

Introduction
Carbon fabrics, tapes and fibers are widely used in aerospace manufacturing, aircraft manufacturing, automotive, due to their high specific characteristics [1-3]. The values of specific strength and specific stiffness for titanium alloys are 30 and 200, respectively, whereas for CFRP these characteristics are at least 90 and 1050. The benefits of carbon plastics also include unique thermal characteristics. Modern technologies for the molding of parts and products from carbon plastics, for example, vacuum infusion, ensure the specified quality while significantly reducing the cost of production [4-6].

To impart functional properties to CFRPs, technologies are used to apply thin metallic coatings to the surface of carbon fabrics [7]. The main purpose of metallization is to change the microstructure and physicochemical properties of the surface of carbon fabrics, which allows to regulate their reactivity, wear resistance, thermal and electrophysical properties, biocompatibility, etc.

The properties of metallized carbon fabrics and carbon plastics based on them are investigated by experimental methods that are laborious and expensive [8, 9]. The task of creating a mathematical model of an elementary carbon filament, on the surface of which a thin metallic coating is applied, is relevant because it will allow modeling the behavior under load of various systems. When conducting a simulation of the stress-strain state of a metal-coated filament, we used the method of solving inverse problems. A distinctive feature of solving inverse problems (as compared with direct problems) was the difference in cause-effect relationships. Creating adequate mathematical models will significantly reduce the path from the idea to the experimental design sample. In this paper, the task was to determine the values of displacements at known values of breaking load. This formulation of the problem was related to the fact that earlier [7], the values of breaking loads and displacements for given loads were experimentally found.

The purpose of this paper is to develop mathematical models that allow predicting the stress-strain state of filaments with a metallic coating.

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Objects and Methodology
The research object is a domestic unidirectional carbon tape LUP, to which a metal coating of stainless steel 12X18H10T was applied by way of magnetron sputtering. Before applying the metal coating, plasma-chemical treatment of the carbon tape was performed. The thickness of the coating was determined directly on the filament using an atomic force microscope of the brand SOLVER47PRO.
To carry out mechanical tests, the carbon tape was divided into filaments, which were tested on a Favimat + Textechno tensile testing machine. A feature of this equipment was its high accuracy and the possibility, along with the magnitude of the breaking stress under tension, elongation and modulus, also to determine the diameter of the filaments and the linear density.
The model of the filament was built using the Siemens NX program; all calculations were performed using the NX / Nastran software package. When building a geometric model, the diameter of the filament was assumed to be 6 μm, its length varied from 10 to 100 microns. Calculations of the stress-strain state of a filament with a change in its length were carried out in order to compare the results of theoretical and experimental analyses. In tensile tests, especially when using Textechno with the Favimat + prefix, the length of each filament was not measured and, in fact, was a random value. A load of 200-5000 cN was applied to the model in the form of a distributed tensile force. On the opposite side of the sample the embedment was used.

Results and Discussion
The model of an elementary thread with a metallic coating is shown in Figures. Calculations of the stress-strain state of the filament (without a metallic coating and with a coating) were carried out for filaments of various lengths. These calculations were performed in order to compare the results of theoretical and experimental studies. In experimental studies, the length of each filament was not measured and, in fact, was a random value. The calculation showed that with an increase in the length of the filament, the values of displacements in their absolute value practically do not change, but are redistributed along its length. When conducting mechanical tests, the magnitude of the maximum strain at which the filament is destroyed was determined. For the convenience of comparing the theoretical and experimental results, the displacement values obtained by calculation were recalculated into a strain.
The results of experimental and theoretical studies are given in the Table.

Table 1. Results of theoretical and experimental studies

| Coating thickness (nm) | Strain (%) | Stress (MPa) |
|------------------------|------------|--------------|
| Calculation results    |            |              |
| Without coating        | 0.78       | 1900         |
| 50                     | 0.67       | 2050         |
| 100                    | 0.56       | 2210         |
| 200                    | 0.40       | 2562         |
| Results of experimental studies | | |
| Without coating        | 0.78       | 1773         |
| 40-80                  | 0.73       | 1893         |
| 140-210                | 0.48       | 1912         |
The calculation showed that with an increase in the length of the filament, the values of displacements in their absolute value practically do not change but are redistributed along its length. The magnitude of the elongation at which the rupture of the filament occurs is 0.78%, which is fully consistent with the results of experimental studies. Thus, as a result of a comparison of theoretical and experimental data, it has been established that the created filament model is adequate.

From the obtained research results it also follows that with an increase in the thickness of the coating, the magnitude of the strain decreases, and the stress values, on the contrary, increase. The nature of the theoretical laws obtained corresponds to the general laws obtained as a result of experimental studies, but they differ in their quantitative estimates.

Fig.1. Model of an elementary thread with a metal coating at magnification x100 (a) and x500 (b)

This difference is probably due to the lack of methods for determining the exact values of the thickness of metallic coatings directly on the filament. The study of the structure of the coatings, carried out using an atomic force microscope, made it possible to establish that the stainless-steel coating represents granules ranging in size from 20 to 200 nm. Such a large variation in the size of the granules leads to a significant difference in the thickness of the metallic coating.
The equipment used for mechanical testing allows determine the value of the linear density of filaments. The results of the analyses show that the average linear density of the filament without a metallic coating is 4.9 tex. With an increase in the thickness of the metal coating, the value of the linear density also increases for a coating with a thickness of 50 nm is 5.0 tex, and with a coating thickness of 100 nm it is 6.5 tex. Thus, the greater the thickness of the metal coating is, the lower the weight efficiency of such materials is and, therefore, it is not advisable to increase the thickness of the metal coating more than 100 nm.

Conclusions
The mathematical model of a metal-coated filament has been developed, which makes it possible to estimate the stress-strain state. The experimental studies carried out confirmed the adequacy of the theoretical model created. As a result of the calculations, it was established that with an increase in the thickness of the coatings from 50 nm to 200 nm, the strain characteristics of the filaments decrease, the stresses increase and the linear density increase. Using the methods of atomic force microscopy, we could not accurately estimate the thickness of the metal coating directly on the filaments, due to the inhomogeneity of the coating. The results obtained can be used in predicting the properties of reinforced fabrics with various metallic coatings, including not only carbon, but glass or basalt ones.

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