Investigation of the mechanical properties of polymer composite materials with various types of hybrid matrices in the extreme conditions of the Arctic

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Abstract. The technology of manufacturing carbon plastics samples with various types of hybrid matrices is presented, one of the components of which is completely cured, and the second (technical wax, anaerobic and organosilicon polymer materials) retains its viscoelastic state after forming products, which ensures a change in the mechanical properties of structural materials. The possibility of using carbon plastics with various types of hybrid matrices for the manufacturing of mechanical engineering products that are used in extreme Arctic conditions is studied. A method for conducting mechanical tests to determine the tensile strength of carbon plastics samples with various types of hybrid matrices at temperatures \( t_1 = 20 \pm 2 ^\circ \text{C}, t_2 = -30 ^\circ \text{C}, t_3 = -50 ^\circ \text{C} \). The results of changes in the strength and deformation properties of carbon plastics with different types of hybrid matrices at negative and positive temperatures compared to the values of the same indicators of carbon plastics without viscoelastic components in the matrix are presented and analyzed.

1. Introduction

Currently, polymer composite materials (PCM) are one of the main structural materials used for the manufacture of large-sized and small body parts, but structurally complex, critical parts of machines and mechanisms [1]. The widespread use of PCM in various industries is due to the ability to create products from them with specified physicomechanical, thermophysical, dielectric, and other properties. High corrosion resistance, strength and low density of PCM make them the most preferred materials for the manufacture of cases, bodies, cabs, frames, fuel tanks, high-pressure cylinders (for cars running on gas fuel) and many other machine parts [1].

Increasing the pace of the development of the Arctic zone and achieving the goals of the state policy of the Russian Federation in the Arctic [2], among other tasks, require the attraction of significant production resources to improve the transport network, in particular, road construction equipment and technological equipment. Extreme natural and climatic conditions, including low air temperatures and strong winds, are features of the Arctic zone of the Russian Federation that influence the formation of state policy in the Arctic [3, 4].

Average sub-zero temperatures in the Arctic range from -4 to -25°C, and the minimum temperatures sometimes drop to -55… -60°C, which makes it necessary to test PCMs used in the production of machine parts and mechanisms at temperatures that allow working in these conditions.

A team of authors, for the production of machine parts operating under alternating loads, has
proposed a technology for the production of PCMs with various types of hybrid matrices, one of the components of which is cured, and the second retains its viscoelastic state after the forming of products [5].

The viscoelastic components of the matrix, like the binder in materials of living nature (for example, in plants, bone, wood), can increase the deformation and strength properties of PCM [6]. The purpose of this study is to determine the dependence of the change in the strength properties of PCMs with different types of hybrid matrices, in particular, the tensile strength, on the ambient temperature: $t_1=20\pm 2^\circ C$, $t_2=-30^\circ C$, $t_3=-50^\circ C$.

2. Materials and manufacturing technology samples

Biaxial carbon fabric based on T300 carbon fiber was chosen as the reinforcing material for PCM samples with various types of hybrid matrices. Elan-Tech EC 57 epoxy resin was used as a binder (for creating products that require increased thermal stability) with a W61 hardener (in a ratio of 100:16 by weight), which ensures the viability of the resin + hardener compound of 70 ... 80 minutes. Based on the analysis of the curing kinetics, the following materials were selected as viscoelastic components of the hybrid matrices: technical wax, anaerobic (Loctite 638) and organosilicon (Unisil-9628) polymer materials.

The samples were made using prepreg technology by vacuum forming: 4 layers of carbon fabric were pre-impregnated with an epoxy binder and laid out on a prepared glass tooling; between 3 and 4 layers along the carbon fabric base thread, the material of a viscoelastic component (~5 mm wide) was applied at a distance of 50 mm from each other; sacrificial and absorbent fabrics were laid on top of the laid layers, after which a vacuum bag was formed and a vacuum discharge was created. The samples were cured under the influence of infrared radiation using the Trommelberg IR3C Standard installation, which provides heating to a temperature of +80±2°C. The resulting carbon fiber sheets were cut into individual samples by mechanical means, followed by processing the edges with a binder.

Four series of flat rectangular carbon fiber samples were produced for mechanical testing:

Series 1: reference sample-carbon fiber without viscoelastic components in the matrix (sample size was 20x250x1,3);

Series 2: carbon fiber with a hybrid matrix, the viscoelastic component of which is an anaerobic polymer material (Loctite 638) (specimen size was 20x250x1,3);

Series 3: carbon fiber with a hybrid matrix, the viscoelastic component of which is a two-component organosilicon polymer material (Unisil-9628) (sample size was 20x250x1,3);

Series 4: carbon fiber with a hybrid matrix, the viscoelastic component of which is technical wax (sample size was 20x250x3,4).

Each series of samples was made in three sets:

- the 1st set of samples was not exposed to negative temperatures and was stored at a temperature of $t_1=20\pm 2^\circ C$;
- the 2nd set of samples was kept in a PozisFH-258-1 freezer at a temperature of $t_2=-30^\circ C$ for 60 days;
- the third set of samples was kept in a LOIP FT-311-80 liquid cryothermostat at $t_3=-50^\circ C$ for 30 days.

In the cryostat, medical ethanol was used as a working fluid (heat carrier), and air was used in the freezer.

The elastic, rheological and strength characteristics of PCM are determined not only by the mechanical properties and the type of components, but also by the conditions of interaction at the interface and the interaction between the elements [7]. The considered viscoelastic components in the composition of the hybrid matrix form an independent PCM phase, with the formation of boundary layers with a reinforcing material and a binder material.

3. Test procedure

The samples were tested in accordance with GOST RU 56785-2015 «Polymer composites. Tensile
method for flat specimens» using the machine for testing structural materials «UTS 110M-50» and using the temperature testing system «STI TS 3» (for samples subjected to pre-exposure at negative temperatures). Before testing at temperature $t_2=-30^\circ C$ and $t_3=-50^\circ C$, the samples were kept at the corresponding temperature for 60 minutes. The test speed was $V=2$ mm/min for all samples.

4. Discussion of test results
The tests performed allowed us to obtain the values of absolute breaking forces and tensile strength of the manufactured series of samples at temperatures: $t_1=20\pm2^\circ C$, $t_2=-30^\circ C$, $t_3=-50^\circ C$. The average values of these indicators are shown in Table 1.

| Holding and test temperature | Matrix type of carbon plastics samples | Tensile strength, MPa | Absolute breaking strength, N |
|-----------------------------|--------------------------------------|-----------------------|-------------------------------|
|                             | without viscoelastic components       | with anaerobic polymer material | with organosilicon polymer material | with technical wax * |
| $t_1=20\pm2^\circ C$        | 1803                                  | 1907                  | 1288                          | 557 |
|                             | 46866                                 | 49584                 | 33494                         | 37900 |
| $t_2=-30^\circ C$           | 1356                                  | 1371                  | 1159                          | 414 |
|                             | 35266                                 | 35651                 | 30134                         | 10783 |
|                             | 1269                                  | 1274                  | 1226                          | 134 |
| $t_3=-50^\circ C$           | 32990                                 | 33113                 | 31873                         | 9125 |

* In a comparative assessment of the mechanical properties of carbon plastics with various types of hybrid matrices, an adjustment should be made for the scale factor of the samples (samples of carbon fiber with technical wax in the matrix with the same width had a thickness of 2.6 times more than the other samples).

Carbon plastics samples with an anaerobic polymer material in the matrix have the highest average tensile strength at both positive and negative temperatures, which is explained by the nature of interfacial interactions at the «fiber-binder-anaerobic polymer material» interface. The monomers included in the composition of anaerobic polymers, which are acrylic and methacrylic acids and amides of unsaturated acids, contribute to an increase in adhesion [8], which explains the higher average value of the ultimate strength for a given series of samples, as well as a small spread in the values of this indicator at a temperature $t_1=20\pm2^\circ C$ (Table 1).

When the temperature decreases, the properties of the anaerobic polymer material change (the recommended storage temperature for Loctite 638 is in the range of 8 ... 21°C, and transportation is allowed at a temperature not lower than -16°C). Presumably, this factor negatively affects its adhesive properties. Reducing the adhesive strength in the «fiber-binder-anaerobic polymer material» system at temperatures $t_2=-30^\circ C$, $t_3=-50^\circ C$ increases the value of the unbiased point estimate of the dispersion of the parameters monitored during tests by almost 2 times. However, the value of the ratio of dispersion to the mathematical expectation of ultimate strength remains within 5% (Table 1). This is a good indicator and allows predicting the properties of PCMs with this type of hybrid matrix with a sufficient degree of reliability in the manufacture of products operating under negative temperatures.

An analysis of the data obtained during mechanical tests allows us to make an unambiguous conclusion that low temperatures lead to a decrease in the mechanical properties of PCMs both with various types of hybrid matrices and PCMs without viscoelastic components in the matrix. At the same time, it should be noted the intensity of the decrease in the studied indicators for various types of PCM. So, after holding in a freezer and testing at a temperature of $t_3=-30^\circ C$ for samples without viscoelastic components in the matrix, there is a decrease in the average value of the ultimate strength by 25% is observed. For samples with anaerobic polymer material and technical wax in the matrix, respectively, by 28 % and 26%. The smallest decrease in the average value of the ultimate strength in comparison
with the samples not exposed to low temperatures is observed in PCM with an organosilicon polymer material in the matrix - by 10%.

After holding the samples in a cryothermostat and testing them at a temperature of $t_3=-50^\circ$C, for carbon plastics without viscoelastic components and with an anaerobic polymer material in the matrix, a decrease in the average value of the ultimate strength by 30% and 33%, respectively, is observed in comparison with the samples of these series, which were exposed to low temperatures. The greatest decrease in the average value of the tensile strength compared to this indicator for samples that were not exposed to low temperatures is observed in carbon plastics with technical wax in the matrix – by 76%.

Of particular interest are samples with an organosilicon polymer material in the matrix, since for these samples at a temperature of $t_3=-50^\circ$C, there is a minimal decrease in the controlled indicator - by 5% compared to samples of this series that were not exposed to low temperatures. At the same time, in comparison with the samples of this series tested at a temperature of $t_2=-30^\circ$C, at $t_3=-50^\circ$C, an increase in the average value of the ultimate strength by 5% is recorded.

Various physical properties of polymers (mechanical, electrical, magnetic, optical, thermal) are determined by the processes of molecular mobility occurring in them. These processes depend on the structural features of their chains and structural organization [9].

Insignificant, in comparison with other series of samples, the change in the average value of the ultimate strength of carbon plastics samples with an organosilicon polymer material in the matrix with decreasing temperature can be explained from the standpoint of the structure of organosilicon polymers. In these materials, the main chain is made up of silicon and oxygen atoms, and the side groups contain atoms of carbon, hydrogen or other chemical elements, which makes organosilicon compounds have increased thermal and chemical resistance [9].

In the process of testing at a temperature of $t_2=-30^\circ$C, samples of carbon plastics with an organosilicon polymer material in the matrix are destroyed in the most mechanically stressed places with lower breaking forces. However, the adhesive strength of organosilicon polymers increases during cooling [10]. This leads to an increase in the adhesion strength in the "fiber-binder-organosilicon polymer material" system and, as a consequence, to a slight increase in the average value of the ultimate strength of this type of samples at a temperature $t_3=-50^\circ$C, as well as a decrease in the value of the unbiased point estimate of the variance of this indicator (table 2).

| Holding and test temperature | without viscoelastic components | Matrix type of carbon plastics samples | with anaerobic polymer material | with organosilicon polymer material | with technical wax |
|-----------------------------|---------------------------------|---------------------------------------|-------------------------------|----------------------------------|------------------|
| $t_1=20\pm2^\circ$C         | 217.01                          | 35.95                                 | 158.77                        | 109.18                           |
| $t_2=-30^\circ$C            | 12.04                           | 1.89                                  | 12.25                         | 19.59                            |
|                             | 36.7                            | 65.55                                 | 59.5                          | 30.21                            |
| $t_3=-50^\circ$C            | 2.7                             | 4.78                                  | 5.13                          | 7.2                              |
|                             | 85.54                           | 61.13                                 | 53.26                         | 22.98                            |
| Unbiased point variance estimate | 6.74                           | 4.8                                   | 4.35                          | 17.13                            |

Technical wax with a carbon plastics impregnated with a binder forms a mechanical bond, which is carried out due to the mechanical engagement of the irregularities of the contacting surfaces and the pressure that is created by a vacuum bag when the formation of samples. At a temperature of $t_2=-30^\circ$C, the technical wax in the composition of the carbon fiber matrix freezes, but the mechanical connection with the reinforcing material remains. The sharp decrease in the average value of the ultimate strength of specimens of this series at a temperature of $t_3=-50^\circ$C (table 1) is explained by the complete loss of
plasticity by the technical wax. After holding in a cryothermostat, the technical wax became brittle and crumbly, due to which the mechanical connection with the reinforcing material was completely lost. The absence of a plastic layer led to the loss of deformation properties and weakening of the material as a whole.

An important characteristic of the viscosity and deformation of a material during fracture is the elongation at fracture $\delta$. The average values of the relative elongation in fracture of carbon plastics samples with different types of hybrid matrices and without viscoelastic elements in the matrix at temperatures $t_1=20\pm 2^\circ C$, $t_2=-30^\circ C$, and $t_3=-50^\circ C$ are presented in table 3.

### Table 3. Average values of elongation at fracture of carbon plastics samples with different types of hybrid matrices

| Matrix type of carbon plastics samples | Holding and test temperature, $t_1=20\pm 2^\circ C$ | Holding and test temperature, $t_2=-30^\circ C$ | Holding and test temperature, $t_3=-50^\circ C$ |
|---------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| without viscoelastic components       | 5.3                             | 4.9                             | 4.5                             |
| with anaerobic polymer material       | 5.7                             | 5.6                             | 4.6                             |
| with organosilicon polymer material   | 5.5                             | 5.0                             | 4.7                             |
| with technical wax *                  | 7.1                             | 4.4                             | 4.0                             |

The viscoelastic components in the PCM hybrid matrix form internal interfaces, the strength of which is less than $1/5$ of the total adhesion strength of the material. This is the main condition for the implementation of the crack braking mechanism at the interface according to Cook-Gordon [11-13]. The presence of weak internal surfaces, contrary to expectations, does not weaken the material as a whole, but strengthens it, making it viscous like living wood or bone. This allows us to explain the higher values of the relative elongation of samples with different types of hybrid matrices at a temperature of $t_1=20\pm 2^\circ C$ and decrease in the value of this indicator at temperatures $t_2=-30^\circ C$, $t_3=-50^\circ C$ due to freezing of viscoelastic components and their destruction.

When assessing the mechanical properties of carbon plastics with different types of hybrid matrices and their changes under the influence of negative temperatures, not only strength and deformation characteristics, but also the character of the destruction of samples are important (table 4).

### Table 4. Description of the nature of destruction of carbon plastics samples with different types of hybrid matrices

| Matrix type of carbon plastics samples | Character of destructions |
|---------------------------------------|---------------------------|
|                                       | Holding and test temperature, $t_1=20\pm 2^\circ C$ | Holding and test temperature, $t_2=-30^\circ C$ | Holding and test temperature, $t_3=-50^\circ C$ |
| without viscoelastic components       | Longitudinal splitting in the working area (found in the grippers), transverse fracture under the grippers | Longitudinal splitting in the working area, lateral destruction under the jaws | Longitudinal splitting in the working area (found in the grippers), lateral destruction under the grippers |
| with anaerobic polymer material       | Longitudinal splitting in the working area (found in the grippers), transverse fracture occurs under the grippers | Longitudinal splitting in the working area, lateral destruction under the jaws | Longitudinal splitting in the working area, lateral destruction under the grips |
| with organosilicon polymer material   | Longitudinal splitting in the working area (found in the grippers) | Longitudinal splitting in the working area, lateral destruction under the grippers | Longitudinal splitting in the working area, lateral (oblique) fracture under grips |
| with technical wax *                  | Longitudinal splitting in the working area and in the grippers | Longitudinal splitting in the work area and in the grippers or slippage in the grippers | Longitudinal splitting in the working area and in the grippers |
At low temperatures, PCMs are characterized by such fracture mechanisms as: cross-cracking of the matrix, disruption of the interlayer gap, peeling and destruction of fibers [14].

Figures 1-3 show photographs of carbon plastics samples tested at temperatures $t_1=20\pm2^\circ\mathrm{C}$, $t_2=-30^\circ\mathrm{C}$ and $t_3=-50^\circ\mathrm{C}$. For samples (with the exception of carbon plastics with technical wax in the composition of a hybrid matrix), when tested for tensile tests at negative temperatures, severe cracking along the fibers of the base used in the manufacture of carbon plastics samples is characteristic.

Figure 1. Carbon plastics samples after tensile testing at $t_1=20\pm2^\circ\mathrm{C}$: a – without viscoelastic components; b – with anaerobic polymer material; c – with organosilicon polymer material; d – with technical wax

Figure 2. Carbon plastics samples after holding and tensile tests at $t_2=-30^\circ\mathrm{C}$: a – without viscoelastic components; b – with anaerobic polymer material; c – with organosilicon polymer material; d) with technical wax
Figure 3. Carbon plastics samples after holding and tensile tests at $t_3=-50^\circ\text{C}$: a – without viscoelastic components; b – with anaerobic polymer material; c – with organosilicon polymer material; d) with technical wax

5. Conclusion

With a decreasing in temperature, the destruction of carbon plastics of all series occurs at lower stresses and is accompanied by intense cracking of the surface.

Carbon plastics with an anaerobic polymer material in the composition of the hybrid matrix, when passing to the region of negative temperatures, has the best tensile strength, stable and maximum (compared to the samples of the other series) elongation at fracture at a temperature of $t_2=-30^\circ\text{C}$, and also comparatively high value of this indicator at $t_3=-50^\circ\text{C}$ (2% higher compared to carbon plastics without viscoelastic components in the matrix).

Tests of carbon plastics with an organosilicon polymer material as part of a hybrid matrix showed a slight decrease in the tensile strength (by 10% and 5% at temperatures $t_2=-30^\circ\text{C}$ and $t_3=-50^\circ\text{C}$, respectively), while for this series of samples the maximum the value (in comparison with the samples of the other series) of the relative elongation at fracture at a temperature of $t_3=-50^\circ\text{C}$ (4% higher compared to carbon plastics without viscoelastic components in the matrix).

The samples of carbon plastics reinforced plastic with technical wax in the composition of the hybrid matrix at a positive temperature have a maximum relative elongation at fracture compared to the samples of the remaining series (20 ... 25% higher). However, in the region of negative temperatures, this type of specimen showed the highest rate of decline and the worst values of both deformation and strength properties.

Thus, the use of carbon plastics with anaerobic and organosilicon polymer materials in the composition of hybrid matrices in the design and production of mechanical engineering products operating in the Arctic, will provide higher strength and deformation properties of machine parts compared to carbon plastics without viscoelastic components in the matrix.

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