Investigation of mechanical characteristics of a carbon-ceramic composite material based on a braided preform

A N Baryshev¹, G G Kulish¹, A A Smerdov¹, I A Timofeev² and S V Tsvetkov¹
¹Bauman MSTU, Russia, 2nd Baumanskaya Str., 5, 105005, Moscow, asmerdov@mail.ru
²JSC “Kompozit”, Pionerskaya Str., 4, Korolev, Moscow Region, 141070, Russia

Abstract. An experimental analysis of characteristics of a carbon-ceramic composite material based on a braided preform in a plane stress state was carried out. The technical limits of strength and elastic characteristics of the material are determined. Tests of tubular specimens in a complex stress state allowed us to obtain the data necessary for the construction of the failure criterion. The possibilities of using various failure criteria of the composite are investigated. The contours of the surface of the strength of the material in the space of stresses at the intersection of its coordinate planes are built.

Keywords: Experiment, tubular specimen, carbon-ceramic composite, failure criterion

Introduction
Carbon-ceramic composite materials (CCrCM) for temperature resistance and mechanical characteristics are close to carbon-carbon composite materials (CCbCM), but they are able to work for a long time at high temperatures in oxidizing environments [1, 2]. An important feature of hightemperature composite materials based on carbon fibers is a weak change in the strength and elastic characteristics in a wide temperature range [3]. This allows to significantly simplify the process of experimental analysis and conduct tests without heating.

The starting material for the manufacture of CCrCM is usually a billet of CCbCM, the matrix of which is saturated with silicon carbide during processing. Form, basic geometrical dimensions of the product and the structure of the filler are stipulated at the stage of making preforms and carbon-carbon blanks. The conventional method for the production of carbon-fiber reinforced plastics is the creation of shell parts — “winding” is limited for creating a reinforcing base of high-temperature composite materials in connection with the difficulty of forming carbon and ceramic matrices in dense non-intertwined filament structures. A promising and high-performance method for manufacturing shell-type parts from high-temperature composite materials is the contour weaving on the forming tool [4]. Carbon-silicon carbide matrix can form by both a gas-phase method, providing materials with low porosity and a high content of SiC, but having a low performance, and a liquid-phase method, which features higher performance and lower costs [1, 2, 5-7].

Purpose and methodology of the experiment
The purpose of the experimental analysis was to determine the elastic and strength characteristics of the CCrCM braided frame, as well as the selection of the failure criterion that correctly describes the This work is licensed under the Creative Commons Attribution 3.0 Unported License. To view a copy of this license, visit http://creativecommons.org/licenses/by/3.0/ or send a letter to Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.
process of failure in a plane stress state. Due to the high sensitivity of the characteristics of composites to manufacturing technology for the production of the specimens manufacturing techniques of standard products should be applied. It is also necessary that the stress-strain state of the working part of the specimen is uniquely determined by the applied force factors, and the failure occurs within the working area.

These requirements are fully satisfied with thin-walled tubular specimens, used in this study. The sample drawing is shown in Figure 1.

![Figure 1. Thin-walled tubular sample and the direction of the axes](image)

Tubular specimens of CCrCM type Cf / (C-SiC) m are made in JSC “Kompozit”, Korolev. The reinforcing filler: carbon fiber YKH-M-3K. Volume fraction of carbon fiber: ≈52%. Matrix: pyrolytic carbon, pyrolytic silicon carbide. Reinforcement pattern is 0/±70°. Silicon carbide content: ≈32% of the mass. Sizes of experimental samples: internal diameter 45 mm, height 185 mm, wall thickness: ≈ 1.9 mm. The braided preform of the specimen is formed by a system of skeletal filaments located along the generatrix and braid filaments located at angles $\varphi = \pm 70^\circ$ to the generatrix. Figure 1 shows the coordinate system in which all the results are presented. Axis 1 is directed along the generatrix, axis 2 - in the circumferential (transverse) direction. The edges of the sample are supported by a winding made of a polymer composite material.

Tubular specimens were loaded with tensile and compressive force in the axial direction, external and internal pressure, as well as torque. These types of tests allow to determine the full set of technical characteristics of strength and elasticity of the material for the case of a plane stress state. The method and results of tests of tubular specimens from CCrCM manufactured at JSC “Kompozit” are given in [8].

When testing tubular specimens in a complex stress state, the data necessary to construct a failure criterion were obtained. During the study, biaxial compression, biaxial stretching, joint stretching in the axial direction and compression in the circumferential direction, joint compression in the axial direction and stretching in the circumferential direction, joint stretching and shear in the axial direction were realized.

To measure strains, strain gauges were used, glued to the lateral surface of the specimen in the axial direction, in the circumferential direction and at an angle of 45° to the generatrix. When during testing the sample was subjected to external pressure, the sensors were placed on the inner surface of the specimen.

In tensile tests along the axis and in torsion, normal stresses in the direction of axis 1 and tangential stresses in the plane 12 were created in the material respectively. For fixing the sample the specialized equipment was used for the testing machine. The transfer of the axial load on the sample was carried out using self-tightening collet grips, while the torque was transmitted using pins.

During compression in the axial direction, the specimen was freely mounted on the plates of the testing machine, and in the material in the direction of the axis 1, compressive stresses were created. To
ensure uniformity of the stress field in the circumferential direction, a load was applied through a spherical support. When testing for internal and external pressure, the specimen material was loaded for tension and compression in the direction of the axis 2, respectively. Since the design of the specimen does not provide for the presence of a sealing layer, the loading was carried out through an elastic sealing shell. Devices are made in such a way that the axial component of the load does not affect the specimen. For the tensile and compression tests in the axial direction, combined with the compression in the circumferential direction, an experimental device, shown in Figure 2, has been developed and manufactured.

![Device for the joint loading of tubular specimens with axial force and external pressure](image)

**Figure 2.** Device for the joint loading of tubular specimens with axial force and external pressure

The external pressure acting on the specimen in the chamber of the developed device can reach 40 MPa, and the maximum force transmitted to the sample is 150 kN. The axial force is controlled independently of external pressure. A structurally similar device is described in [9], but the developed version allows for a wider range of possible load paths.

**Experimental results**
Strength and elastic characteristics were determined as the average value of the results for tests of at least three specimens. Characteristics are shown in Table 1.
Table 1. Characteristics of CCrCM.

| Characteristics                                                      | Value  |
|----------------------------------------------------------------------|--------|
| Ultimate tensile strength along the axis X + 1, MPa                  | 174.9  |
| Modulus of tensile elasticity along the axis E1, GPa                  | 38.7   |
| Poisson's ratio in tension along the v12 axis                         | 0.137  |
| Compressive strength along the axis X -1, MPa                         | 140.3  |
| Modulus of elasticity in compression along the axis E1, GPa            | 41.0   |
| Poisson's ratio in compression along the v12 axis                     | 0.157  |
| Tensile strength in tension in the circumferential direction X + 2, MPa| 414.7  |
| Modulus of tensile elasticity in the circumferential direction E2, GPa| 87.3   |
| Poisson's ratio in tension in the circumferential direction v21       | 0.170  |
| Compressive strength in the circumferential direction X-2, MPa         | 234.2  |
| Modulus of elasticity in compression in the circumferential direction E2, GPa | 80.7 |
| Poisson's ratio in compression in the circumferential direction v21   | 0.277  |
| Strength at shear X12, MPa                                           | 90.4   |
| Shear modulus G12, GPa                                               | 16.4   |

From Table 1 it follows that the tensile strength of the material significantly exceeds the compressive strength. The discrepancy between the values of elastic characteristics, determined under tension and under compression, is not more than 8%.

Figure 3 shows a typical stress-strain diagram in the longitudinal direction. Diagrams for other types of stress have close to linear character until the moment of failure.

The characteristic appearance of the failed specimens is shown in Figure 4.

**Figure 3.** The characteristic pattern of the strain under longitudinal tension.

**Figure 4.** View of failed specimens: a) under loading with external pressure; b) in torsion; c) under loading with internal pressure; d) when stretching along a generatrix.

The results of strength tests under complex stress conditions are given in Table 2.
Construction of material strength criterion

When studying the failure process of a composite material, two approaches are possible: micromechanical [11, 12, 13] and phenomenological [14]. To apply the micromechanical approach, it is necessary to study the properties of the matrix and the filler. Given the fact that the CCrCM matrix is formed directly during the manufacture of the material, separate study of its properties is difficult. The development of strength criteria for composite materials for various types of stress state is the subject of a large number of works [15, 16, 17]. In practice, the criteria of the Mises-Hill, Tsai-Wu, Tsai-Hill, Hashin, maximum stresses and maximum strains and others are widely used [16, 18].

The strength of the material studied can be described using various criteria. Let us consider some of them:
- criterion of maximum stress;
- modified Mises-Hill criterion; - Tsai-Wu criterion.

The maximum stress criterion is formulated as:

\[
\begin{align*}
X_{-1} & \leq \sigma_{11} \leq X_{+1} \\
X_{-2} & \leq \sigma_{22} \leq X_{+2} \\
|\sigma_{12}| & \leq X_{12}
\end{align*}
\]  

(1)

The expression for the modified Mises-Hill criterion is:

\[
\frac{\sigma_{11}^2}{\sigma_{1B}} - \frac{\sigma_{11}\sigma_{22}}{\sigma_{1B}\sigma_{2B}} + \frac{\sigma_{22}^2}{\sigma_{2B}^2} + \frac{\sigma_{12}^2}{\sigma_{12B}^2} = 1
\]  

(2)

where \(\sigma_{1B}, \sigma_{2B}\) are strength limits in direction 1 and 2, chosen according to the type of stress state \((\sigma_{1B}=X_{1} at \sigma_{11}>0, \sigma_{1B}=X_{1} at \sigma_{11}<0, \sigma_{2B}=X_{2} at \sigma_{22}>0, \sigma_{2B}=X_{2} at \sigma_{22}<0), \sigma_{12B}=X_{12}\). Tsai-Wu criterion:
where \( F_1, F_{11}, F_2, F_{22}, F_{12}, F_{66} \) are constants determined by test results, and \( F_1, F_{11}, F_2, F_{22}, F_{66} \) are uniquely determined through the technical limits of material strength, and \( F_{12} \) is selected from the condition of the best description of the experimental data obtained complex stress state [18].

Figure 5 shows the contours of the surface strength in the planes \( \sigma_{11}-\sigma_{22}, \sigma_{11}-\sigma_{12} \) and \( \sigma_{22}-\sigma_{12} \).

The resulting contours and surface strengths meet the requirements: are simply connected, closed, and intersect the coordinate axes at points corresponding to technical strengths [18]. All considered criteria qualitatively correctly describe the behavior of the material in a series of experiments. To quantify the quality of the criteria, we introduce a measure of the deviation from the experimental points obtained under a complex stressed state:

\[
\Delta = \sum_k \left( \frac{s_i^* - s_i}{s_i^*} \right)^2
\]

where \( k \) is the number of experimental points obtained under a complex stress state, \( s_i \) is the distance from the origin of coordinates \( O \) in the stress space \( \sigma_{11}-\sigma_{22}-\sigma_{12} \) to the experimental point \( P_k \), \( s_i^* \) is the distance from the origin to the point of intersection of the \( OP_k \) beam with the surface strength.

For the Tsai-Wu criterion, the calculated deviation was 0.717, for the modified Mises-Hill criterion it was 0.735, and the minimum deviation value achieved using the maximum stress criterion was 0.472. Thus, among the options considered, the maximum stress criterion the best describes the strength of the material studied.
Conclusions

The characteristics of the CCrCM with a reinforcement pattern of ± 70°/0° in the plane stress state are investigated. It is established that the strength of the material in the plane stress state is satisfactorily described by the maximum stress criterion. In the presence of additional experimental data, it becomes possible to carry out a procedure for identifying the characteristics of reinforcing elements and a matrix for performing calculations for products with an arbitrary reinforcement pattern.

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