Automated assembly of small cell rod preforms

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Abstract. The paper presents the results of the development and implementation of the technology for the production of spatially reinforced preforms with rectilinear fibers. Automated technology is used for preforms with small cell structure. The results of assembling the preforms are presented, the possibility of switching to an even smaller cell size is substantiated, ways of increasing the density of preforms are discussed.

Improvement of the technology of production of Carbon-Carbon Composite Materials (CCCM) worldwide is one of the priority areas that determine the defense capability and scientific and technical potential of the state owning them, with special attention being paid to automation of technological processes. The creation of modern structures used in high-temperature conditions and high thermomechanical loads is not effective without the use of parts from CCCM. The application of CCCM significantly expanding the resources of the operability of structures and increasing their profitability.

The highest thermomechanical characteristics of parts from CCCM are obtained with a uniform, straight-line arrangement of carbon wisps without damage in the material, compatibility of the matrix and fibers in the material. Stability and reproducibility of properties is determined by the level of technological preparation of production. At the current stage of development of the technique and technology of manufacturing the CCCM it is important to increase the reproducibility and stability of the material properties at a high level by automating technological processes. Reduce the size of the repeating cell and increase the density of the preform. Increase labor productivity and reduce the harmful impact on equipment operators.

The process of automated assembly of small cell rod preforms is complex and difficult to implement. At the initial stage of the research work, options of realization of the preform assembly process were determined by analogy with the assembly of preforms from 1.2 mm rods [1]. Two methods are chosen: styling of the rods of the measured length from the hopper and feeding the long rod with a roller into one flow. It is not possible to determine which of these methods is the best, based on theoretical studies, due to the large number of uncertainties, therefore, when designing the installation, common and different nodes were identified for each assembly method. Designing of experimental rigging was carried out with an equal opportunity of realization of each of the considered methods. The installation is shown in figure 1.

The diameter of the rods used and the rod spacing in the guide plates determine the density of the resulting preform. It is difficult to manually assemble the preform with a rod spacing less than twice the maximum size of the rods, and it is impossible in an automated way, due to the emerging resistance of the passage of the horizontal rod from vertical rods. For a set of statistics on the diameters of the resulting rods from the UMT40-3K-EP wisp in two additions to the investigated pultrusion rod making machine, an optical micrometer LСтен-7 / 50-485-I4-2 were installed. The
measurements were carried out on three flows in three planes on each flow, the obtained values for the flows differed insignificantly. The average diameter of the serially produced rod was 0.709 mm, the minimum was 0.653 mm, and the maximum was 0.779 mm. The distribution of rod diameters is normal. On the basis of measurements, it can be concluded that the actual dimensions of the rods are 0.71 ± 0.04 mm. The difference in diameters of the ellipse is about 0.034 mm.

Figure 1. Experimental installation

To determine the linear density of the rod from the UMT40-3K-EP, 200 m of the rod were weighed in two additions, the resulting linear density of the rod Tx (c) = 392.25 tex. Accordingly, the WVC (polyvinyl chloride insulation connection wire) content in the rod is 32.25 tex.

Let’s determine the influence of the technological parameters of the preform assembly - vertical rods spacing and rod layers spacing, on the density of the preform. In figure 2, the thickness of the selected repeating element in all structures is equal to the layers spacing (hc). Vertical rods spacing in the direction perpendicular to the feed of the rods is denoted as hz.

Figure 2. Calculation schemes of repeating preform element

The density of the preform is determined as the ratio of the weight of the rods in the selected volume to the selected volume for each structure (1).
\[ \rho_{4D} - l = \frac{\sqrt{3} T(x)(hc + 0.5hz)}{h^2hc \cdot 10^3} \]
\[ \rho_{3L} = \frac{T(x)(hc + hz)}{h^2hc \cdot 10^5} \]  

In addition, we recalculate the change of the selected cells, if we switch to the use of rods of optimal shape, while preserving the parameters of filling the rod with fiber and its linear density. For the preform of the 3D structure, the optimal cross-section of the rod in all reinforcement directions is a square. For the preform of the 4D-I structure, the optimal cross-section of the vertical rods is the regular hexagon, and for the horizontal - the square.

The calculations are performed for the case when \( hz = 2hc \), but can be recalculated for other relations. The results of calculating the density of preforms \( \rho \) and the density of preforms without WVC \( \rho' \), calculated by replacing the linear density of the rod by twice the linear fiber density, are given in Table 1.

### Table 1. Results of calculating the density of preforms

| 4D-I round rod |            |            |            |            |            |            |
|----------------|------------|------------|------------|------------|------------|------------|
| \( hz, \text{ cm} \) | 0.136      | 0.138      | 0.140      | 0.142      | 0.144      | 0.144      | 0.140      |
| \( hc, \text{ cm} \) | 0.068      | 0.069      | 0.07       | 0.071      | 0.072      | 0.068      | 0.068      |
| \( \rho, \text{ gr/cm}^3 \) | 0.7346     | 0.7135     | 0.6932     | 0.6739     | 0.6553     | 0.6746     | 0.7035     |
| \( \rho', \text{ gr/cm}^3 \) | 0.6742     | 0.6548     | 0.6363     | 0.6185     | 0.6014     | 0.6191     | 0.6456     |

| 3D round rod |            |            |            |            |            |            |
|---------------|------------|------------|------------|------------|------------|------------|
| \( hz, \text{ cm} \) | 0.136      | 0.138      | 0.14       | 0.142      | 0.144      | 0.144      | 0.14       |
| \( hc, \text{ cm} \) | 0.068      | 0.069      | 0.07       | 0.071      | 0.072      | 0.068      | 0.068      |
| \( \rho, \text{ gr/cm}^3 \) | 0.6362     | 0.6179     | 0.6004     | 0.5836     | 0.5675     | 0.5897     | 0.6122     |
| \( \rho', \text{ gr/cm}^3 \) | 0.5839     | 0.5671     | 0.5510     | 0.5356     | 0.5208     | 0.5413     | 0.5618     |

| 3D square rod |            |            |            |            |            |            |
|---------------|------------|------------|------------|------------|------------|------------|
| \( hz, \text{ cm} \) | 0.1205     | 0.1223     | 0.1241     | 0.1258     | 0.1276     | 0.1276     | 0.124      |
| \( hc, \text{ cm} \) | 0.0603     | 0.0612     | 0.0620     | 0.0629     | 0.0638     | 0.0603     | 0.0603     |
| \( \rho, \text{ gr/cm}^3 \) | 0.8101     | 0.7867     | 0.7644     | 0.7430     | 0.7226     | 0.7509     | 0.7794     |

| 4D-I optimal rod |            |            |            |            |            |            |
|------------------|------------|------------|------------|------------|------------|------------|
| \( hz, \text{ cm} \) | 0.1205     | 0.1223     | 0.1240     | 0.1258     | 0.1276     | 0.1276     | 0.1241     |
| \( hc, \text{ cm} \) | 0.0589     | 0.0598     | 0.0606     | 0.0615     | 0.0624     | 0.0589     | 0.0589     |
| \( \rho, \text{ gr/cm}^3 \) | 0.9463     | 0.919      | 0.893      | 0.8680     | 0.8441     | 0.869      | 0.9063     |

When vertical rods spacing changes, the force interaction of the fed rod with vertical rods changes. For automated assembling, the interaction of the rods with interference is not allowed, therefore the vertical rods spacing should not be less than twice the diameter of the rod with the upper value of the tolerance field.

Let’s analyze the possibility of increasing the filling of the rod with fiber by reducing the diameter, for example, rods with a diameter of 0.7 mm from two additions of UMT40-3K-EP. Analyzing the photographs of the cross-section of the rods on a scanning electron microscope [2], it can be concluded that the filaments have a nearly circular cross-sectional shape, a close diameter. If we accept the assumption that the filaments are round and of equal diameter, we obtain a calculated filament diameter of 6.57 μm. In work [3] the calculation of porosity is given for various filament laying schemes. We will predict the minimum diameter of the rod, if we assume that filaments are located in the rod according to this scheme, the result is given in Table 2.
Table 2. Minimum rod diameter and porosity for various laying schemes filament.

| Laying name | Laying scheme | Porosity, % | Volumetric share of carbon fibers, % | Diameter of the rod, mm |
|-------------|---------------|-------------|--------------------------------------|-------------------------|
| Trigonal    |               | 9,4         | 90,6                                 | 0,532                   |
| Quadrangular|               | 21,5        | 78,5                                 | 0,561                   |
| Hexagonal   |               | 39,6        | 40,4                                 | 0,6                     |
| Test rod    |               | 48,74       | 51,26                                | 0,71                    |

Analyzing the results shown in Table 2, we see that the serially produced rod has about 48% porosity, and there are reserves for its reduction. Knowing the WVC content in the rod is 32.25 tex and its bulk density of 1.19 g / cm³, we determine that WVC occupies 13.3% of the area of carbon filaments. Practically achievable is the diameter of the rod from the UMT40-3K-EP filament in two additions ≈0.65 mm with a decrease in the ellipse to 0.02.

When using rods with a diameter of 0.65 mm, it is possible to reduce the distance between the vertical rods to 1.3 mm and the layers spacing to 0.65 mm. The theoretical density of the 4D-I skeleton will be increased from 0.67 g / cm³ to 0.8 g / cm³, and when using the rods of the optimal cross-section of the same density, the density of the 4D-I skeleton may reach 0.90-0.94 g / cm³.

In the process of assembling the preform, the rods are fed by feeding units in turn from a special device. The control system monitors the length of the inserted rod and its smooth passage through the preform. The positioning of the rod feed units is performed by stepping drives with feedback. Zero positions of the rod feed units are determined by inductive limit sensors. In the feeding unit, a pruning mechanism is installed, eliminating the possibility of undercutting the rod, increasing the quality of the cut and reducing damage to the end of the rod. The knife drive is moved beyond the feeding unit.

To eliminate the fractures of the horizontal rods and deviations along the length of the supplied rod, a rod passing sensor is installed through the preform. The rod is fed to the specified depth before the sensor triggers, then returns to the distance from the sensor to the preform and is cut off. In case of failure of the sensor, when feeding a rod of a given length, an error is given. The optical rod passing sensor is located on the opposite side and moves in concert with the transverse movement of the feeding unit.

With the application of the control of the execution of each transition, with the laying of horizontal rods, and independent control of the two feeders, a transition to a non-linear (with branched algorithm) control scheme of the installation was carried out. The control system is implemented on a programmable logic controller with an external operator touch panel. Information about the process flow is displayed on the touch panel. With the help of the touch screen monitor you can control the assembly process and see which nodes perform movements on the control program.

The control program of the installation is performed on a programmable logic controller with duplication of all transmitted and received data to the computer to document the process and display on the monitor, in the form of highlighting of individual elements on the screen.

The program can be executed in automatic and debug mode. In debug mode, the preform assembly constants are introduced and the control files are updated.
The complex of equipment upgrading made it possible to create equipment oriented to the serial assembly of small cell rod preforms with a diameter of up to 360 mm and a height of up to 500 mm.

The testing of the automatic assembly modes has been carried out and some techniques have been developed for performing the transitions, preparing the rigging, and eliminating possible failures in assembling the preforms. Three preforms of reduced size were assembled - a diameter of 145 mm, the height of a set of layers of horizontal rods was 200 mm in automatic mode. Laying time of layers by one feeding device is 32 hours. The productivity of the assembly has been increased by 2 times in comparison with manual assembly, the influence of harmful factors of carbon dust on collectors has been reduced. The preforms correspond to the requirements for small cell rod preforms; preforms density was 0.675 g / cm$^3$. The probability of defects of a preform on insufficient passage of a rod through a preform and hinges of a rod is eliminated by the installation of the rod passage sensors. The reserves for shortening the duration of fabrication of preforms and increasing their density were revealed.

It is revealed that this assembly technology does not allow for the automatic laying of 20 mm to the bottom of the preform and 30 mm to the top. These allowances can be taken into account when determining the size of the rods used to install vertical rods or to be laid manually.

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