У період технологічної підготовки і початкових стадій освоєння в серійному виробництві композитних виробів має місце досить велика кількість і різноманітність технологічних дефектів. Рівень цих дефектів часто перевищує допустимий за вимогами конструкторської документації і, отже, призводить до браку виробів. Найбільш характерним технологічним дефектом для композитних конструкцій, армованих безперервними волокнами або тканинними матеріалами, є відхилення товщини формованого композиту від її проектного значення. Іншим видом характерних дефектів є локальні порушення цілісності в дискретних об'ємах полімерних композиційних матеріалів у вигляді порожнин, що виникають при формуванні його паковки в технологічному формотворному оснащенні. Проведено аналіз і обґрунтування полів допусків на ці типи технологічних дефектів. Встановлено допуски на відхилення товщини виробу, що формується, від проектного значення. Показано, що вхідний контроль визначає реалізоване в препрезі відхилення товщини від номіналу для одношарового напівфабрикату. Відхилення в товщині паковки від номіналу включає складові, які виникають при її формуванні. Ці складові пов'язані з інтегральними відхиленнями технологічного режиму формування (тиск, температура та їх зміна в часі) від регламентованого відповідною документацією. Отримано аналітичні залежності щодо обґрунтованого призначення полів допусків для фізико-механічних характеристик полімерного композиційного матеріалу, що має відхилення в товщині, при наявності в ньому локальних порушень суцільності у вигляді порожнеч. На відміну від існуючих моделей, отримані залежності дозволили оцінити якість технологічних процесів формування напівфабрикатів і виробів з полімерних композиційних матеріалів за рівнем дефектів розглянутого класу. Проведено аналіз впливу дефектів даного класу на фізико-механічні характеристики полімерного композиційного матеріалу. Показано, що при використанні для виготовлення виробу армуючого матеріалу з паспортними полем допуску значення об'ємного вмісту волокон завжди знаходиться в його інтервалі. У той же час відхилення об'ємного вмісту зв'язуючого може виходити за межі свого паспортного поля допуску

Ключові слова: композит, формоутворення, відхилення товщини, порушення цілісності, поля допусків, фізико-механічні характеристики

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DETERMINATION OF THE INFLUENCE OF DEFLECTIONS IN THE THICKNESS OF A COMPOSITE MATERIAL ON ITS PHYSICAL AND MECHANICAL PROPERTIES WITH A LOCAL DAMAGE TO ITS WHOLENESS

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1. Introduction

Advanced state-of-the-art technology is characterized by constant increase of the volumes of polymer composite materials (PCMs) used worldwide, which urges developers to achieve their more advanced technical and economic characteristics [1]. Along with the undeniable advantages of PCMs over other structural materials, composites also have a number of disadvantages, including the impossibility of creating «defect-free» structures in advance [2]. It is known that various types of defects in structures with PCMs negatively affect their functional properties, which are especially critical for products of various classes of technology. Elements of composite structures in the process of manufacturing undergo many technological effects, both thermal and mechanical [3, 4]. Many of these defects are the result of insufficient performance in a number of technological processes in experimental production and errors in the design documentation [5, 6]. Other defects are due to the lack of equipment, deviations in technological regimes, and the influence of the human factor directly in production [7, 8]. The most characteristic technological defect for composite structures reinforced with continuous fibres or fabric materials is the deviation in the thickness of a moulded PCM from its design value [9, 10]. This discrepancy in the thickness of the composite as to the design appears during the technological operations of impregnating the prepreg binders or in the formation of the package and reduces the physical and mechanical properties (PMPs) of the PCM in the local area of the appearance of this defect and the load-carrying capacity of the product as a whole [11]. Another type of characteristic defects is local violations of integrity in discrete volumes of PCMs in the forms of pores and voids that appear when making the package in technological forming equipment. Local violations of integrity in the form of voids are microscopic air pores formed during the package-making with incomplete removal of solvent vapour from the binding element [11].

The level of technological defects associated with these influences often exceeds the permissible design documentation requirements and results in a significant expansion of the PCM PMPs and, consequently, in the absence of composite products. Therefore, the analysis and justification of the tolerance fields for these types of technological defects is an urgent problem.

2. Literature review and problem statement

At different times, many authors discussed the types of technological defects in composite structures, for example [12–19]. The traditional simulation of the physical state of a PCM consists in explicit representation of the considered defects in the model. Thus, for the study of the influence of such defects as hollowness, the theory of inclusions is usually used, in which inclusion has zero properties [12]. However, such assessments were inadequate in certain cases, as was shown in [13]. In [13], in contrast to work [12], when studying a defect in the form of a void, it is proposed to locally shift the PCM fibre to accommodate it. More precise consideration of the influence of emptiness and its placement on the PCM PMPs is given in [10]. In [14], there is a systematic numerical study of the effect of hollowness on the size of the bundle which is thus formed. In [15, 16], a two-dimensional model of the violation of the integrity of structural elements with PCMs is considered. In these studies, the quasi-static destruction of layered plates is analysed in the presence of elliptical voids between monolayers. In papers [17–19], the buckling of monolayers of a rectangular form are analysed. Work [20] also contains the results of large studies conducted using finite-element analysis software packages. Most models investigate the development of a «permissible» deviation, which means a defect the shape and size of which allow the product to function for a certain time. During this time, this defect develops, increasing its size up to its destruction.

However, it is necessary to provide conditions for the manufacture of composite structures that would not lead to a significant increase in the size and quantity of defects. That is, it is essential to maintain the size and number of defects in the field of allowable values throughout the life of the products to ensure a regulated spread of the PCM PMPs. In this case, the simulation of the physical state of a PCM should consist in the averaging of heterogeneities without explicit representation of the defects in the model, as is done, for example, in papers [21, 22]. Thus, in [22] the averaging of defects is carried out as to their volumetric content. However, the results found in this work relate only to composite materials obtained by carbonization with their conversion into carbon-carbon material.

Only such an approach to modelling helps evaluate the properties of PCMs and structures on their basis on the whole. Under these conditions, it is possible to establish reasonable tolerances for the PMPs of monolayers and composite packages, which will enable to evaluate the quality of the technological processes of their formation.

3. The aim and objectives of the study

The aim of the study is to identify patterns of technological processes in the formation of composites, which will ensure the reduction of the influence of technological defects of PCMs on the distribution of their PMPs. To achieve this aim, the following objectives were set and done:

– to find out the interaction of technological factors in the formation of PCMs and their joint effect on their final PMPs;

– to obtain analytical dependences for the purposeful assignment of tolerance fields for the PMPs of monolayers and composite packets having deflection in the thickness, in the presence of local destructions of continuity in the forms of pores and voids.

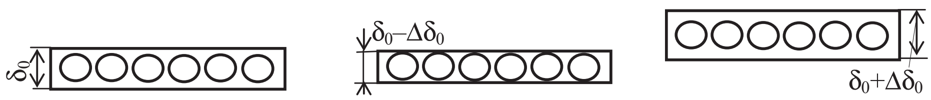
4. Materials and methods of studying the intereffect of technological factors in the production of composites on their physical and mechanical properties

Research on technological defects of PCMs and the reasons for their occurrence is carried out on the basis of methods of technological mechanics of composites. In this case, the PMPs of unidirectional PCMs are determined on the basis of mathematical models of the theory of reinforcement with the addition of increments of corresponding characteristics within them within the limits of their passport interval of tolerances. For structures consisting of three directions of reinforcement (0°, ±φ°, 90°), the tolerance fields are established based on the dependence derived from the model of V. V. Vasiliev [22, 23].

5. Detection of the intereffect of technological factors in the production of composites on their physical and mechanical properties

The thickness of the monolayer δ_0 depends on the technology of forming the package and its initial state [4, 10]. If the formation is carried out with impregnation of the binding tape, the prepreg, then the volume content of the fibres Θ_f and the binding element Θ_b must be realized within it within the tolerance. Otherwise there is a defect of the deflection of the thickness from the nominal. The defect is manifested either before the formation of the product at the stage of input control or in the finished product [24, 25]. The unit section of the fragment of the thickness of the prepreg has the form shown in Fig. 1.

In the first case, it is caused by violations of the regulations on the impregnation of the semifinished product (prepreg) associated with the deviation of the «pressure-time» regime (p–τ), «temperature-time» regime (T–τ), general violation of the regime (p, T–τ) or deviation of the rate of impregnation, that is, the «τ» mode [5, 9, 12]. As an example, these tolerances are given for carbon tapes (Table 1) [26].



a *b* *c*

Fig. 1. Possible types of cross-sections of prepreg after impregnation:
a – normal: $\Delta\delta=0$, $\Delta\Theta_b=0$; *b* – with refinement: $\Delta\delta<0$, $\Delta\Theta_b<0$; *c* – with thickening: $\Delta\delta>0$, $\Delta\Theta_b>0$

Table 1

Properties of carbon tapes and unidirectional epoxy carbon fibres on their basis

Type of the tape	Width of the tape, mm	Linear density, g/m	Density of the thread in the tape, g/cm^3	Number of threads per 10 cm, not less	Properties of epoxy hydrocarbon					
					Density ρ, g/cm^3	Content of the filler Θ_f, % vol.	Bending strength *F*, GPa	Tensile strength F^+, GPa	Modulus of elasticity during bending *E*, GPa	Monochrome thickness δ_0, mm
LU-P	255±25	35±3	1.69	460	1.53	63±4	–	–	165±20	0.10±0.01 0.13±0.02
LU-P-0.1-A	255±20	30±5	1.69	460±25	1.49	62±4	0.7	0.7	157±25	0.1...0.12
LU-P-0.1-B	255±20	30±5	1.69	460±25	1.49	62±4	0.6	0.7	157±25	0.1...0.12
LU-P-0.2-A	255±20	30±5	1.69	485±25	1.49	62±4	0.7	0.7	157±25	0.11...0.15
LU-P-0.2-B	255±20	30±5	1.69	485±25	1.49	62±4	0.6	0.7	157±25	0.11...0.15
ELUR-A	245±30	30±5	1.71	420±25	1.50	63±4	0.9	0.9	145±(20...25)	0.11...0.13
ELUR-P-B	245±30	30±5	1.71	420±25	1.50	63±4	0.8	0.8	145±(20...25)	0.11...0.13

The normal cross section has an error corresponding to the tolerance guaranteed by the supplier of reinforcing semi-finished product Δδ. This tolerance is related to the deviation of the linear density of the reinforcing semifinished product (the number of threads per 10 cm wide) and, as a consequence, with the volume content of the reinforcing semifinished product Θ_f under the control (passport) production of a unidirectional prepreg.

It is easy to establish the relationship between the thickness increments and the relative volumetric content of the fibres and the binder.

The volume of a single structural element is equal to:

$$V=\delta\cdot 1\cdot 1. \quad (1)$$

The increase in the volume of a single structural element is:

$$\Delta V=\Delta\delta\cdot 1\cdot 1. \quad (2)$$

The volume of a single structural element consists of fibre and binder volumes:

$$V=V_f+V_b. \quad (3)$$

According to (1) and (3), we obtain:

$$\delta=V_f+V_b. \quad (4)$$

In the general case:

$$\Delta\delta=\Delta V_f+\Delta V_b. \quad (5)$$

Dividing (5) by (1), we obtain:

$$\frac{\Delta\delta}{V}=\frac{\Delta\delta}{\delta}=\frac{\Delta V_f}{V}+\frac{\Delta V_b}{V}$$

or

$$\Delta\bar{\delta}=\Delta\theta_f+\Delta\theta_b. \quad (6)$$

It is known [27, 28] that:

$$\theta_f+\theta_b=1. \quad (7)$$

In this case,

$$\left(\theta_f\pm\Delta\theta_f\right)+\left(\theta_b\pm\Delta\theta_b\right)=1\pm\left(\Delta\theta_b+\Delta\theta_b\right).$$

The desired connection between Δδ and increments $\Delta\Theta_f$ and $\Delta\Theta_b$ can be obtained from (6):

$$\Delta\delta=\left(\Delta\theta_f+\Delta\theta_b\right)\delta. \quad (8)$$

Analysing Table 1, it is easy to establish, for example, for a prepreg based on a tape LU that Δδ=±0.01 mm at δ=0.1 mm and Θ_f=0.63±0.04, where $\Delta\Theta_f$=±0.04. From (8) we obtain $\Delta\Theta_b$=±0.06.

Thus, there may be a case at $\Delta\Theta_f$=0.04, $\Delta\Theta_b$=0.06 $\left(\theta_f+\theta_b\right)+\left(\Delta\theta_f+\Delta\theta_b\right)=1.1$ and $\left(\theta_f+\theta_b\right)-\left(\Delta\theta_f+\Delta\theta_b\right)=0.9$.

$$\left(\theta_f+\theta_b\right)-\left(\Delta\theta_f+\Delta\theta_b\right)=0.9.$$

Thus, the field of tolerance as to the prepreg from this tape is based on the volume content of the fibres $\theta_f=0.63^{+0.04}_{-0.04}$, and with the binding element, it is $\theta_b=0.37^{+0.06}_{-0.06}$.

In the general case, $\theta_f=\theta^{n+\Delta\theta^n_f}_{f-\Delta\theta^n_f}$, $\theta_b=\theta^{n+\Delta\theta^n_b}_{b-\Delta\theta^n_b}$. Thus,

$$\Delta\delta_0=\delta_0\left(\Delta\theta^n_f+\Delta\theta^n_b\right),$$

where $\Delta\theta^n_f$ and $\Delta\theta^n_b$ are passport values of the increments $\Delta\Theta_f$ and $\Delta\Theta_b$.

The defect of local integrity destruction in the forms of pores and voids is modelled by the reference to the relative volumetric content of the PCM components – fibres Θ_f and the binding factor Θ_f of the third component, the relative volumetric content of the pores and voids, $\Delta\Theta_p$, similarly to study [22].

Then, in accordance with the rule of mixtures [27, 28], equality (7) will take the form:

$$\theta_f + \theta_b + \theta_p = 1 \tag{9}$$

or

$$\theta_f + \theta_b = 1 - \theta_p = \chi, \tag{10}$$

where $\chi < 1$.

When forming a PCM structure, the developer seeks to implement as much as possible the relative volumetric fibre content, as it is known that the reinforced component of the PCM provides a high level of PMPs to the composite [3, 11, 12]. However, depending on the type of fibre location in the PCM section (packing density), a certain $\theta_{f\,\max}$ can be implemented in the material, after which it ceases to be monolithic. Its PMPs are directed to zero values (Fig. 2) [3, 9, 12].

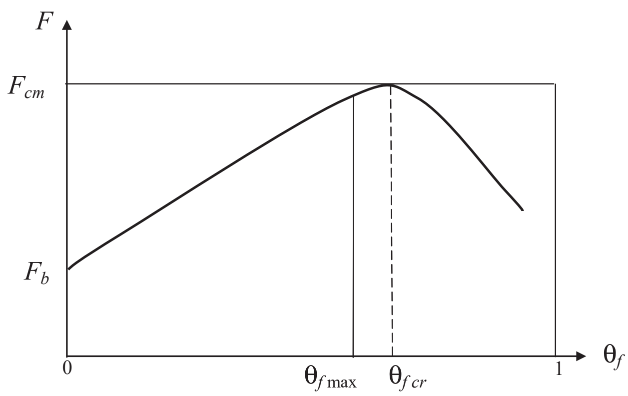


Fig. 2. The conditional dependence of the PCM strength limit on the expansion of F_{cm} on the relative volume of fibres Θ_f: F_b is the binding strength of the binder; $\theta_{f\,cr}$ is the critical relative volume content of the fibres

It is known that for an ideal tetragonal arrangement of fibres in the cross section of the PCM, $\theta_{f\,cr}$=0.785, and with hexagonal, it is $\theta_{f\,cr}$=0.907 [23]. However, as a result of the technological limitations inherent in the methods of product formation and possible deviations, the maximum relative volume content of fibres is usually regulated as $\theta_{f\,\max} < \theta_{f\,cr}$. This excludes access to the subcritical area of the PCM PMPs. Usually, $\theta_{f\,\max}$ lies within the range of 0.55...0.65 [23, 26].

The PMPs of a unidirectional PCM are determined on the basis of approximate formulae based on the theory of reinforcement [23, 28] with the addition of an increase in corresponding characteristics within them within the passport tolerance interval. Since the presence of voids Θ_p does not change the initial volume content of the fibres, according to (10) the PMPs of unidirectional PCMs with their passport increments will be determined by the formulae replacing 1 by $\chi < 1$ in applications that reflect the contribution of the binder to this property.

The unit of elasticity of a unidirectional PCM along the fibres is:

$$\left(E_x \pm \Delta E_x\right) = E_{f\,-\Delta E_f^n}^{\;+\Delta E_f^n} \cdot \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n} + E_{b\,-\Delta E_b^n}^{\;+\Delta E_b^n}\left(\chi - \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n}\right). \tag{11}$$

Here and hereafter, ΔR_i^n is the passport deviation from the R i-th characteristic rating.

Poisson's ratio when stretching and compressing along the fibres is:

$$\left(\nu_{xy} \pm \Delta\nu_{xy}\right) = \nu_{f\,-\Delta\nu_f^n}^{\;+\Delta\nu_f^n} \cdot \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n} + \nu_{b\,-\Delta\nu_b^n}^{\;+\Delta\nu_b^n}\left(\chi - \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n}\right). \tag{12}$$

The tensile strength of the compression along the fibres essentially depends on which component of the PCM collapses earlier: the fibre or the binder (matrix) (Fig. 3).

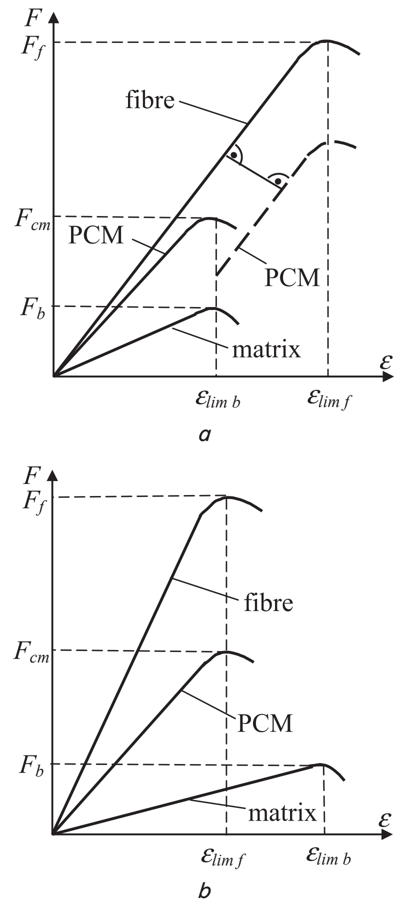


Fig. 3. The conditional load diagrams of a unidirectional PCM along the fibres: *a* — at $\varepsilon_{\lim b} < \varepsilon_{\lim f}$; *b* — at $\varepsilon_{\lim b} > \varepsilon_{\lim f}$

If the boundary deformation of the binder is less than the limiting strain of the fibres $\varepsilon_{\lim f}$ (Fig. 3, *a*), then the first matrix is destroyed [30]. Then

$$\left(F_x \pm \Delta F_x\right) = \frac{F_{b\,-\Delta F_b^n}^{\;+\Delta F_b^n}}{E_{b\,-\Delta E_b^n}^{\;+\Delta E_b^n}}\left[E_{f\,-\Delta E_f^n}^{\;+\Delta E_f^n} \cdot \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n}\right] +$$

$$+\, E_{b\,-\Delta E_b^n}^{\;+\Delta E_b^n}\left(\chi - \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n}\right) \approx F_{b\,-\Delta F_b^n}^{\;+\Delta F_b^n}\frac{\left(E_x \pm \Delta E_x\right)}{E_{b\,-\Delta E_b^n}^{\;+\Delta E_b^n}}; \tag{13}$$

with $\varepsilon_{\lim b} > \varepsilon_{\lim f}$ (Fig. 3, *b*)

$$\left(F_x \pm \Delta F_x\right) = F_{f\,-\Delta F_f^n}^{\;+\Delta F_f^n}\theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n} +$$

$$+\frac{E_{b\,-\Delta E_b^n}^{\;+\Delta E_b^n}}{E_{f\,-\Delta E_f^n}^{\;+\Delta E_f^n}}\left(\chi - \theta_{f\,-\Delta\theta_f^n}^{\;+\Delta\theta_f^n}\right) \approx F_{f\,-\Delta F_f^n}^{\;+\Delta F_f^n}\frac{\left(E_x \pm \Delta E_x\right)}{E_{f\,-\Delta E_f^n}^{\;+\Delta E_f^n}}. \tag{14}$$

Formulae (11)–(14) denote the following: E_b, ν_b, and F_b are the elastic modulus, the Poisson coefficient, and the maximum strength of the binder (matrix); E_b, ν_b, and F_f are the elastic modulus, the Poisson coefficient, and the maximum strength of the fibre; $\pm R^n$ is the passport deviation of the R-th property within the permissible limits.

The displacement modulus of the unidirectional G_{xy} PCM and the limit of its F_{xy} displacement strength are determined by the dependence:

$$\left(G_{xy}\pm\Delta G_{xy}\right)=\frac{G_{f-\Delta G_f^n}^{+\Delta G_f^n}\cdot G_{b-\Delta G_b^n}^{+\Delta G_b^n}}{G_{b-\Delta G_b^n}^{+\Delta G_b^n}\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}+G_{f-\Delta G_f^n}^{+\Delta G_f^n}\left(\chi-\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}\right)};$$

$$\left(F_{xy}\pm\Delta F_{xy}\right)=F_{xyb-\Delta F_{xyb}^n}^{+\Delta F_{xyb}^n}\left[\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}+\frac{G_{b-\Delta G_b^n}^{+\Delta G_b^n}}{G_{f-\Delta G_f^n}^{+\Delta G_f^n}}\left(\chi-\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}\right)\right]. \quad (15)$$

Since the fibres of the reinforcing material and the matrix are isotropic, it can be assumed that $G_f=\dfrac{E_f}{2\left(1+\nu_f\right)}$ and $G_b=\dfrac{E_b}{2\left(1+\nu_b\right)}$ [9, 26]. In addition, in the passports on reinforcing materials and binders, tolerances on their modulus of elasticity and the Poisson coefficients are more often given than on G_f and G_b, and an analogue of this formula can be used instead of formula (15) [9, 28]:

$$\left(G_{xy}\pm\Delta G_{xy}\right)=\frac{E_{f-\Delta E_f^n}^{+\Delta E_f^n}\cdot E_{b-\Delta E_b^n}^{+\Delta E_b^n}}{2\left[\begin{array}{l}E_{f-\Delta E_f^n}^{+\Delta E_f^n}\left(\chi-\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}\right)\left(1+\nu_{b-\Delta\nu_b^n}^{+\Delta\nu_b^n}\right)+\\+E_{b-\Delta E_b^n}^{+\Delta E_b^n}\left(1+\nu_{f-\Delta\nu_f^n}^{+\Delta\nu_f^n}\right)\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}\end{array}\right]}. \quad (16)$$

$$\left(F_{xy}\pm\Delta F_{xy}\right)=F_{xyf-\Delta F_{xyf}^n}^{+\Delta F_{xyf}^n}\left[\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}+\frac{E_{b-\Delta E_b^n}^{+\Delta E_b^n}\left(1+\nu_{f-\Delta\nu_f^n}^{+\Delta\nu_f^n}\right)}{E_{f-\Delta E_f^n}^{+\Delta E_f^n}\left(1+\nu_{b-\Delta\nu_b^n}^{+\Delta\nu_b^n}\right)}\right]. \quad (17)$$

The modulus of elasticity of a unidirectional PCM across the fibres at tensile-compression is determined by the formula:

$$\left(E_y\pm\Delta E_y\right)\approx\frac{E_{f-\Delta E_f^n}^{+\Delta E_f^n}}{\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}+\dfrac{E_{f-\Delta E_f^n}^{+\Delta E_f^n}}{E_{b-\Delta E_b^n}^{+\Delta E_b^n}}\left(\chi-\theta_{f-\Delta\theta_f^n}^{+\Delta\theta_f^n}\right)}. \quad (18)$$

The strength of the unidirectional PCM across the fibres with tensile-compression, taking into account the shape of the fibre, can be approximated by the formula [9, 28]:

$$\left(F_y\pm\Delta F_y\right)=0.7F_{b-\Delta F_b^n}^{+\Delta F_b^n}. \quad (19)$$

In the case of the formation of a package of unidirectional prepregs, the PMPs of its structure, which consists of three directions of reinforcement – along the direction of the fibres $\varphi_0=0°$, at the angle $\pm\varphi$, and across the fibres $\varphi_{90}=90°$ is determined by the formulae [9, 23, 27, 28]:

$$\left(E_x\pm\Delta E_x\right)=\frac{1}{\left(\delta_0\pm\Delta\delta_o\right)n}\left[\left(B_{11}\pm\Delta B_{11}\right)-\frac{\left(B_{12}\pm\Delta B_{12}\right)^2}{\left(B_{22}\pm\Delta B_{22}\right)}\right];$$

$$\left(E_y\pm\Delta E_y\right)=\frac{1}{\left(\delta_0\pm\Delta\delta_o\right)n}\left[\left(B_{22}\pm\Delta B_{22}\right)-\frac{\left(B_{12}\pm\Delta B_{12}\right)^2}{\left(B_{11}\pm\Delta B_{11}\right)}\right];$$

$$\left(G_{xy}\pm\Delta G_{xy}\right)=\frac{\left(B_{33}\pm\Delta B_{33}\right)}{\left(\delta_0\pm\Delta\delta_o\right)n};\ \left(\nu_{xy}\pm\nu_{xy}\right)=\frac{\left(B_{12}\pm\Delta B_{12}\right)}{\left(B_{22}\pm\Delta B_{22}\right)};$$

$$\left(\nu_{yx}\pm\nu_{yx}\right)=\frac{\left(B_{12}\pm\Delta B_{12}\right)}{\left(B_{11}\pm\Delta B_{11}\right)}, \quad (20)$$

where $(B_{ij}\pm\Delta B_{ij})$ means the generalized rigidity of the multilayer package (packing) and their growth in the orthotropic axes. Therefore, the sum of the corresponding angles of the monolayers is equal to $n_0+2n_{\pm\varphi}+n_{90}=n$. In the case of three directions of reinforcement (n_0, $2n_{\pm\varphi}$, n_{90}),

$$\begin{aligned}\left(B_{11}\pm\Delta B_{11}\right)=&\frac{\left(\delta_0\pm\Delta\delta_o\right)}{\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)}\times\\&\times\Big\{n_0\left(E_1\pm\Delta E_1^n\right)+n_{90}\left(E_2\pm\Delta E_2^n\right)+\\&+2n_\phi\Big[\left(E_1\pm\Delta E_1^n\right)\cos^4\left(\varphi+\Delta\varphi\right)+\\&+\Big[\left(E_2\pm\Delta E_2^n\right)\sin^4\left(\varphi+\Delta\varphi\right)+\\&+2\left(E_1\pm\Delta E_1^n\right)\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\sin^2\left(\varphi+\Delta\varphi\right)\cos^2\left(\varphi+\Delta\varphi\right)+\\&+\left(G_{12}\pm\Delta G_{12}\right)\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)\sin^2 2\left(\varphi+\Delta\varphi\right)\Big]\Big]\Big\};\end{aligned} \quad (21)$$

$$\begin{aligned}\left(B_{22}\pm\Delta B_{22}\right)=&\frac{\left(\delta_0\pm\Delta\delta_o\right)}{\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)}\times\\&\times\Big\{n_0\left(E_2\pm\Delta E_2^n\right)+n_{90}\left(E_1\pm\Delta E_1^n\right)+\\&+2n_\phi\Big[\left(E_1\pm\Delta E_1^n\right)\sin^4\left(\varphi+\Delta\varphi\right)+\\&+\Big[\left(E_2\pm\Delta E_2^n\right)\cos^4\left(\varphi+\Delta\varphi\right)+\\&+2\left(E_1\pm\Delta E_1^n\right)\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\sin^2\left(\varphi+\Delta\varphi\right)\cos^2\left(\varphi+\Delta\varphi\right)+\\&+\left(G_{12}\pm\Delta G_{12}\right)\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)\sin^2 2\left(\varphi+\Delta\varphi\right)\Big]\Big]\Big\};\end{aligned} \quad (22)$$

$$\begin{aligned}\left(B_{33}\pm\Delta B_{33}\right)=&\frac{\left(\delta_0\pm\Delta\delta_o\right)}{\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)}\times\\&\times\Big[\left(n_0+n_{90}\right)\left(G_{12}\pm\Delta G_{12}\right)\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)+\\&+2n_\varphi\Big\{\Big[\left(E_1\pm\Delta E_1^n\right)+\left(E_2\pm\Delta E_2^n\right)-2\left(E_1\pm\Delta E_1^n\right)\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\Big]\times\\&\times\sin^2\left(\varphi+\Delta\varphi\right)\cos^2\left(\varphi+\Delta\varphi\right)+\\&+\left(G_{12}\pm\Delta G_{12}\right)\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)\cos^2 2\left(\varphi+\Delta\varphi\right)\Big\}\Big];\end{aligned} \quad (23)$$

$$\begin{aligned}\left(B_{12}\pm\Delta B_{12}\right)=&\frac{\left(\delta_0\pm\Delta\delta_o\right)}{\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)}\times\\&\times\Big[\left(n_0+n_{90}\right)\left(E_1\pm\Delta E_1^n\right)\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}+\\&+2n_\phi\Big\{\Big[\left(E_1\pm\Delta E_1^n\right)+\left(E_2\pm\Delta E_2^n\right)\Big]\times\\&\times\sin^2\left(\varphi+\Delta\varphi\right)\cos^2\left(\varphi+\Delta\varphi\right)+\\&+\left(E_1\pm\Delta E_1^n\right)\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\left[\sin^4\left(\varphi+\Delta\varphi\right)+\cos^4\left(\varphi+\Delta\varphi\right)\right]-\\&-\left(G_{12}\pm\Delta G_{12}\right)\left(1+\nu_{12-\Delta\nu_{12}^n}^{+\Delta\nu_{12}^n}\cdot\nu_{21-\Delta\nu_{21}^n}^{+\Delta\nu_{21}^n}\right)\sin^2 2\left(\varphi+\Delta\varphi\right)\Big\}\Big].\end{aligned} \quad (24)$$

Here, from the direction of the axis of elasticity 1, the angle of reinforcement j is deducted. This axis corresponds to the direction x, and the axis of elasticity 2 corresponds to the direction y. In formulae (21)–(24), the tolerance mark on the thickness of the monolayer $\Delta\delta_0$ is determined by the final value of the packing thickness: for $\delta_{form}>\delta_{th}$, the sign $\Delta\delta_0$ is positive, and for $\delta_{form}<\delta_{th}$, it is negative. In these formulae, $\Delta\delta_0$ equals:

$$\Delta\delta_0 = \frac{\delta_{form} - \delta_{th}}{n}, \tag{25}$$

where δ_{form} is the thickness of the package after the formation; δ_{th} is the estimated thickness of the package, which is determined by the passport value of the monolayer, excluding deviations from the nominal value, multiplied by the number of monolayers.

6. The results of studying the intereffect of technological factors in the production of composites on their physical and mechanical properties

Let us define the mathematical expectation and the tolerance field of the elastic modulus of a unidirectional PCM along the fibres by formula (11), which is formed from the tape LU-P according to Table 1, with $\theta_f \pm \Delta\theta_f^n = 0.63 \pm 0.04$. Assuming that $\Theta_p=0.1$ and $\chi = 1-\theta_p$, and also that $E_b=(3.3...3.58)$ GPa and $E_f=(200...250)$ GPa [26], we obtain the mathematical expectation $E_b=3.44$ GPa, $\pm\Delta E_b=0.14$ GPa and the mathematical expectation $E_f=225$ GPa, $\pm\Delta E_f=25$ GPa.

Substituting these values in (11), we obtain for the PCM with the presence of a relative number of voids $\Theta_p=0.1$ ($\chi=0.9$) that:

$$\left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\substack{\max\\\max}} = 168.61 \text{ GPa and } \left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\substack{\min\\\min}} = 118.76 \text{ GPa},$$

which corresponds to the tolerance field $\pm\Delta E_x=24.93$ GPa with the mathematical expectation $\pm E_x=143.68$ GPa.

For the elastic modulus of a unidirectional PCM in the absence of voids ($\Theta_p=0$, $\chi=1$) from formula (11), we obtain:

$$\left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\substack{\max\\\max}} = 168.97 \text{ GPa}, \left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\substack{\min\\\min}} = 119.09 \text{ GPa}.$$

The relative loss $E_{x-\Delta E_x}^{+\Delta E_x}$ in the presence of voids makes:

$$\left(\Delta_{E_x}\right)_{\substack{\max\\\max}} = \left[1 - \frac{\left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\chi=0.15\substack{\max\\\max}}}{\left(E_{x-\Delta E_x}^{+\Delta E_x}\right)_{\chi=0\substack{\max\\\max}}}\right]\cdot 100\ \% = $$

$$= \left(1 - \frac{168.61}{168.97}\right)\cdot 100\ \% = 0.21\ \%;$$

$$\left(\Delta_{E_x}\right)_{\substack{\min\\\min}} = \left(1 - \frac{118.76}{119.09}\right)\cdot 100\ \% = 0.28\ \%.$$

It can be expected that the relative losses of PMPs of a unidirectional PCM along the fibres will be insignificant [29]. Thus, for the strength limit of a unidirectional PCM at values of $F_{f-\Delta F_f}^{+\Delta F_f} = 2.1_{-0.1}^{+0.1}$ GPa [26] and the former fields of tolerance of $E_{f-\Delta E_f}^{+\Delta E_f} = 225_{-25}^{+25}$ GPa and $E_{b-\Delta E_b}^{+\Delta E_b} = 3.44_{-0.14}^{+0.14}$ GPa, we obtain that $\left(\Delta_{F_x}\right)_{\substack{\max\\\max}} = 0.14\ \%$ and $\left(\Delta_{F_x}\right)_{\substack{\min\\\min}} = 0.23\ \%$.

The value $\begin{pmatrix}\max\\\max\end{pmatrix}$ corresponds to $-\Delta\theta_f^n$, $(E_f+\Delta E_f^n)$ and $(E_b+\Delta E_b^n)$, and the value $\begin{pmatrix}\min\\\min\end{pmatrix}$ corresponds to $+\Delta\theta_f^n$, $(E_f-\Delta E_f^n)$ and $(E_b-\Delta E_b^n)$ with the substitution in (11).

The relative losses of PMPs of the unidirectional PCM across its fibres with all previous tolerance fields for $\Theta_p=0.1$ are:

$$\left(\Delta_{E_y}\right)_{\substack{\max\\\max}} = 31.29\ \%, \text{ and } \left(\Delta_{E_y}\right)_{\substack{\min\\\min}} = 41.71\ \%.$$

The obtained results indicate a more significant impact of the technological factors considered in the processes of forming a unidirectional PCM across the fibres on the relative losses of its PMP. This is confirmed by some conclusions of work [29].

7. Discussion of the results of studying the intereffect of technological factors in the production of composites on their physical and mechanical properties

When making a prepreg with a passport field, the tolerances ΔQ_f are always in the range $-\Delta\theta_f^n \le \Delta\theta_f \le \Delta\theta_f^n$ while ΔQ_b may go beyond the range of the passport values:

$$-\Delta\theta_b^n \le \Delta\theta_c \le \Delta\theta_b^n. \tag{26}$$

This is the case with an unregulated pressure between the rolls when rolling the prepreg (repressing) $p>[p]$, or at an increased binder viscosity at the time of impregnation $\eta_b>[\eta_b]$.

The binder viscosity may be higher than standard if the rolling temperature is less than the regulated $T<[T]$. Finally, inequality (26) may also occur if the velocity is less than the regulated $V<[V]$ in the rolling process of the reinforcing semifinished product between the rolls.

Consequently, (26) may occur:

– for $p=[p]$, but $T<[T]$ (the reason is low T), as in this case $\eta_b>[\eta_b]$;

– for $p>[p]$, $T=[T]$ (the reason is high p);

– for $p<[p]$, but $T>[T]$ (the reason is high T), as in this case $\eta_b<[\eta_b]$.

Inequality (26) takes place at $\Delta\delta_0 = \delta_0\left(\Delta\theta_f^n - \Delta\theta_b\right)$, where $\Delta\theta_f^n$ is the passport value of $\Delta\Theta_f$; $\Delta\Theta_b$ is the value of $\Delta\Theta_b$ as a result of rolling reinforcing semifinished product (prepreg).

With insufficient compression,

$$\Delta\theta_b > \Delta\theta_b^n. \tag{27}$$

The correspondence of an insufficiently impregnated reinforcing filler to the passport data is checked at the input control by weighing a batch of its samples in length of 1 m at a given width of $(b \mp \Delta b)$. Dividing the average mass of the batch of samples by the area of $S=(b\pm\Delta b)(1\pm\Delta)$, where Δ is the tolerance to the cut width of the sample of 1 m, we obtain the linear density $(\rho\mp\Delta\rho)$ [m/g] regulated in the passport for the supply of the reinforcing material. The linear density $(\rho\mp\Delta\rho)$ should correspond to the value regulated in the passport. If it is less than this value, then the number of threads for 10 cm in width exceeds its passport value and vice versa.

For example, let us consider the tape LU $[\rho\mp\Delta\rho]=$ $=35\pm3$ g/m (Table 1). When entering the control of a batch of samples, it turned out that $(\rho\mp\Delta\rho)=35\pm8$ g/m. Consequently, the number of threads in the tape exceeds the corresponding passport of 460 units by 10 cm.

As noted above, an increase in the relative volumetric content of fibres in the PCM increases its PMPs if this value is $\theta_f<\theta_{f\,cr}$. Upon reaching $\theta_{f\,cr}$, the PCM ceases to be monolithic, since the relative bulk content of the binder $\theta_b=(1-\theta_f)$ will not be sufficient to completely cover the surface of the fibres. In this regard, the excess of the linear density over the passport value is unacceptable. At the same time, the supplier seeks to provide $\theta_{f\,cr}$ as close to as possible to $\theta_{f\max}=[\theta_f+\Delta\theta_f]$. That is, for the tape LU, $\theta_{f\max}$=(63+4) %. For example, at $(\rho\mp\Delta\rho)>[\rho\mp\Delta\rho]$, for the LU of $(\rho\mp\Delta\rho)=34\pm6$ g/m, the PCM PMPs will be lower than the passport guarantee; for example, the elastic modulus at bending is $E<(165\pm20)$ GPa (Table 1).

If a consumer is provided with a prepreg, the regulated value of its thickness during the formation of the monolayer $[\delta_0\pm\Delta\delta_0]$ and the expected (guaranteed) PCM PMPs are indicated in the passport. For example, for an epoxy carbon fibre LU-P-0.1-A (see Table 1), the guaranteed values at $[\delta_0\pm\Delta\delta_0]=0.1...0.12$ mm are the following: the tensile strength is $F^+=0.7$ GPa, the bending strength is $F=0.7$ GPa, and the modulus of elasticity at bending is $E=157\pm25$ GPa [26, 30]. In this case, $[\theta_f\pm\Delta\theta_f]=0.62\pm0.4$.

At the input control, compliance with the passport characteristics is verified by tests of samples made from a prepreg manufactured by the technology that provides $[\theta_f\pm\Delta\theta_f]$, by implementing the thickness equal to $\delta=(\delta_0\pm\Delta\delta_0)n$ and corresponding to the passport value of the PCM PMPs with the permissible tolerances for them (Table 1).

The tolerance field for any i-th characteristic of the PCM $\pm\Delta R_i$ is determined by the task (regulation) of the parameter χ and the known passport values of the tolerance fields included in the characteristic of R_i components of the unidirectional PCM – fibre and binder.

In formulae (19)–(25), the deviation of the PMP parameters of the monolayer $\pm\Delta R_i^n$ corresponds to the permissible passport value. If the deviation module of the thickness of the monolayer $\Delta\delta_0$ can be reasonably assumed to be constant for any monolayer of the package, then such a hypothesis regarding the deviation in the i-th layer $\Delta\varphi_i$ is very rough when manually laying the packaging monolayers. However, with automated presentation, $\Delta\varphi_i$ can be assumed to be a constant, determined by the tolerance field regulated for this equipment, equal to [$\pm\Delta\varphi$].

Under the above conditions of dependence (21)–(24), the tolerance field of any PMP can be determined from (20) as:

$$\Delta R_i=\frac{(R+\Delta R)-(R-\Delta R)}{2} \qquad (28)$$

for further decision on the admissibility of the deviation of the PMPs.

The tolerance fields are also established for violation of the integrity of the PCM in the product in the form of pores (voids) causing a slight decrease in the PCM PMPs under the action of static loads on the product in operation. However, porosity reduces the crack resistance of the product, which leads to a decrease in the product durability [9, 20, 22, 23].

8. Conclusion

1. The interaction of technological factors of PCM formation processes and their joint effect on their final PMPs was revealed and studied. It has been shown that the input control determines the deviation of the thickness from the nominal value for a single-layered semifinished PCM. The deviation in the thickness of the package from the nominal includes the components that appear during its formation. These components are connected with the integral deviations of the technological mode of formation (pressure, temperature, and time change) from those that are regulated by the relevant documentation). If the reinforcing material in the form of a prepreg has passed the input control, defects in the form of deflection of thickness from the nominal value that arise in the process of manufacturing products with the PCM and measured after its formation result in a deviation from the passport values of the PMPs.

2. Based on the formulae of the theory of reinforcement, the fields of tolerances have been obtained as to the physical and mechanical properties of the monolayer and packs of a PCM, which have deflection in the thickness, in the presence of local violations of continuity in the form of voids. An analysis of the influence of the presence of voids on the change in the tolerance fields of the «theoretically nonporous PCM» was carried out.

The obtained dependences help estimate the quality of technological processes of the formation of semifinished products and products of polymer composite materials by the rate of defects of the considered class.

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