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EXPLORING THE POSSIBILITY OF UNDESIRABLE MANUFACTURING HERITAGE REDUCTION IN PARTS MADE OF COMPOSITES AND THEIR JOINTS

The object of the research is the possibility of improving the quality of parts made of composites (CM) by means of pre-polymerization treatment of the wet package with intensive pulse loading. The existing technologies for forming parts from CM involve the compaction of the collected impregnated package of reinforcement layers and their subsequent polymerization under the influence of pressure and temperature. As a result of this technology, residual thermal and shrinkage stresses occur in the composite package, which lead to undesirable spatial deformations of profile parts, a violation of monolithicity in the areas of the connection of the composite and metal ends.

Using the example of an angular composite profile with a profile with doubler on one of the caps, the residual stress calculation is given and the method of choosing rational angles for stacking the reinforcing material is demonstrated in order to reduce the amount of residual thermal stresses that arise in the composite during its polymerization. The dependence of the twisting parameter of a long-dimensional composite profile of constant cross-section along its axis on the modulus of elasticity and the coefficient of linear temperature expansion is plotted. The work explains the mechanism of the emergence of such harmful technological heredity. The value of the residual deformations was estimated.

Based on the analysis of the impregnation process of dry reinforcing material with a binder, the task of increasing the maximum contact area of the binder with fibers is formulated and a possible method of its increase is analyzed. Thus, using the model of capillaries between the fibers of the composite, it is concluded that it is necessary to apply additional pressure to the binder for its deeper advancement between the fibers.

Using a synergistic method of combining knowledge from various branches of industry and based on experimental data, a process of pre-polymerization loading of the impregnated package with intense impulse loading (shock waves) is proposed. This process greatly improves the quality of parts of the units produced.

Keywords: *residual stress, reinforcing material, synergetic method, composites, impulse loading, metal tips.*

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1. Introduction

At various stages of technological transformations, technological heredity is implemented in the production of products from composites (CM) and their connection with metal ends [1]. It can be both useful and harmful. Among the harmful properties of polymerized parts, it is possible to include the appearance of residual stresses that lead to undesirable deformations of parts (warping). In «metal+composite» (M+CM) jointss, under certain production conditions, a violation of the monolithic structure of the CM can be observed in the form of a local decrease in the volume density of the reinforcement or bubbles.

The article evaluates the value of temperature and shrinkage deformations of profiled parts, shows the mechanism of formation of adhesive shrinkage deformations and violation of monolithicity.

The work proposes technological methods that ensure a reduction in the level of harmful technological heredity.

The formation of a spatially cross-linked structure of profiled products made of CM is accompanied by an increase in material density, chemical shrinkage, and the appearance of residual adhesive and thermal compressive stresses, which lead to their significant warping. The general dependencies for estimating shrinkage and temperature deformations are given in [1]. Known methods of managing residual stresses and deformations are reduced to the imposition of a force field on the technological object, tensioning of fittings, pressing. They also use layer-by-layer hardening, control of energy input and output to the reactive mass. This is realized by changing the temperature of the medium surrounding the surface of the product. Radiation and other types of exposure are promising [1–5]. It is necessary to know the level of emerging residual stresses or deformations after each stage of the forming process for their practical implementation.

For example, in source [1] approaches to the assessment of technological stresses and deformations in products made of composite materials are considered, and in [2] attention is paid to the study of thermoelastic stresses in laminated composites composites. In [3, 4], the behavior of thin-walled composite profiles with an open section under the action of thermomechanical loading is considered. The source [5] offers an approach for determining the stress-strain state of a multilayer composite.

When considering the problem of managing residual stresses and deformations in CM products, it is worth paying attention to the possibility of controlling these parameters by changing the structure of the CM package:

- reinforcement angles of monolayers;
- number of monolayers;
- sequence of their stacking;
- use of monolayers of different materials in one package of CM, etc.

Practical quantitative recommendations for technologists regarding the influence of these parameters on the stress-strain state of a thin-walled composite product are practically absent in the literature.

Therefore, *the aim of research* is to improve the quality of parts from CM and M+CM joints by using additional impulse action during their formation.

2. Materials and Methods

2.1. Methods of research. Theoretical methods of mechanics of materials are used to estimate the amount of thermal grooves (twisting) of profiles.

A comparison with the experimental results of compaction of the forming material with explosive explosives is used to evaluate the effectiveness of the preliminary impulse loading of the forming material.

2.2. Accepted assumptions. The degree of warping of the profiles was evaluated assuming the absence of shrinkage of the binder.

When evaluating the effectiveness of the impulse load, the identity of the amplitude-time characteristics of the explosion of explosive substances and the electrohydraulic load was assumed.

3. Results and Discussions

3.1. Deformations of the profiled product. The model for estimating the amount of deformations of a thin-walled composite profile is proposed in [3–5]. It makes it possible to obtain dependencies for the component values of the complete deformation of the profile (longitudinal elongation, linear movement in the vertical and horizontal planes, and twisting) on the physical and mechanical characteristics of the materials of the monolayers that make up the CM package. In general, these dependencies are complex mathematical functions that have a number of local and global extrema.

A angular profile with an profile with doubler on one of its shelves was considered (Fig. 1).

The geometric dimensions of such a profile, necessary for conducting parametric studies, are adopted based on the analysis of existing composite profiles. Let the angular profile 1 and pad 2 be made of KMU-4e carbon fiber plastic, which is quite widely used for the construction of aircraft products. If to assume that the thickness of the carbon fiber monolayer is 0.08 mm, it is possible to estimate the total number of layers that make up the angular profile and the profile with doubler. So, with δ_2=4 mm and δ_3=2 mm, it is possible to state that parts 1 and 2 consist of 50 and 25 layers, respectively. If to assume that the profile with doubler 2 is reinforced at an angle of 0°, and the profile 1 has a structure of symmetrically reinforced material (with a stacking angle ±φ). Such an assumption when choosing the properties of parts is based on the analysis of the structures of the existing nomenclature of power elements of the structure. For preliminary analysis, let's assume that part 1 has a symmetrical structure of reinforcement – 12 layers with a stacking angle of +45° and 12 layers with a stacking angle of –45°. In this case, the modulus of elasticity E_{x1} when stretched along the x axis (Fig. 1) of part 1 is 20 GPa. In this case, the modulus of elasticity E_{x2} when stretched along the x axis of part 2 will be equal to 100 GPa. The coefficients of linear thermal expansion (CLTE) of parts 1 and 2 with the specified reinforcement of parts will be equal to $3.5\cdot10^{-6}$ 1/K and 0 1/K, respectively. Further analysis of the deformed state of the combined profile during its heating is carried out by varying the physical-mechanical and geometric properties of such a structure and a given temperature difference. At a temperature difference ΔT of 150 °C, the proposed model gives a profile twist angle close to zero (0.1° per 1 m of profile length) with a value of the modulus of elasticity E_{x1} equal to 52.07 and 14.6 GPa – zones I and II in Fig. 2. In this case, the following values of the modulus of elasticity of part 1 are achieved when using reinforcement at angles of ±27° and 55°, respectively.

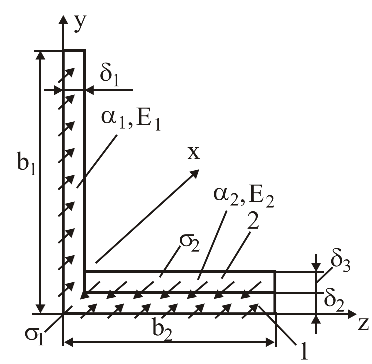

Fig. 1. Sketch of an angular profile with an profile with doubler: 1 – detail with a stacking angle ±φ; 2 – detail with a reinforcement angle 0°; σ – temperature stresses in profile elements

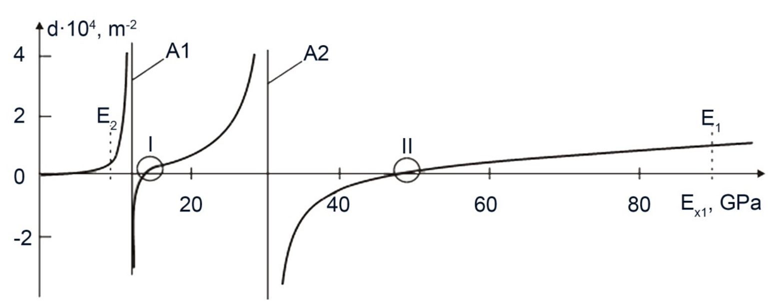

Fig. 2. Dependence of the second derivative on the twist angle of the profile d along the length of the profile on the modulus of elasticity along the x-axis of part 1: $A1$, $A2$ – asymptotes of the function; I, II – regions with sufficiently small twist angles; the range of change of the argument $E_2...E_1$ – the area of the physical content of the properties of part 1, which correspond to the values of the modulus of elasticity of the KMU-4e carbon fiber monolayer along and across the fiber, respectively

At the same time, it is necessary to take into account that the CLTE of such CM packages are $-2.5 \cdot 10^{-6}$ 1/K and $12.2 \cdot 10^{-6}$ 1/K, respectively. In the model used, the deformation of the modulus of elasticity and CLTE are independent parameters, although from a technological point of view, both of these characteristics are functions of the reinforcement angle. In the general case, the twist angle of the profile reaches a value close to zero at different values of j, which leads to the optimum in terms of modulus of elasticity, CLTE, the ratio of the thicknesses of parts 1 and 2, as well as other varying parameters. The choice of the second derivative along the length of the profile from its twist angle as the objective function is due to the with aim to exclude the influence of end fasteners. Fig. 3 shows the dependence of the second derivative of the profile twist angle δ on the profile length from the CLTE of parts 1 and 2, he modulus of elasticity and the thickness (number of monolayers) of part 2. Analyzing these graphs, it follows that the reduction of the twist angle is possible when:

– E_{x2}=38.5 MPa, which corresponds to the reinforcement angle ±33° of part 2, i. e. 12 layers with an angle of +33° and 12 layers with an angle of –33° (at the same time, the CLTE of part 2 is $-2.1 \cdot 10^{-6}$ 1/K and the value of the twist angle increases, but not significantly – from 0.2° to 3° per meter of length);

– the thickness of the profile with doubler 2 is about 0.8 and 2.8 mm (Fig. 3, *c*), which corresponds to 10 layers with 0° reinforcement and 36 layers with 0° reinforcement.

When analyzing the behavior of such dependencies, it is worth remembering that the mathematical dependencies issued by the model may have areas that do not make physical sense. Conclusions (for example, about the possibility of controlling the twist angle of the profile) should be made only based on extremes, which makes physical sense. When designing a product from CM, the recommendations for the designer to reduce the amount of the profile twisting should be compared with similar parameters obtained during the strength analysis of the profile.

In the general case, if the recommended angles of reinforcement of the parts of the composite profile do not coincide, then it is necessary to make some intermediate decision.

The deformations of the profiled product calculated in this way may be less than those that actually occur during their manufacture. This can be explained by the need to account for shrinkage stresses caused by surface tension forces on the contact surfaces of the matrix and reinforcement.

3.2. Formation mechanism and estimation of residual temperature stresses. When filling the capillaries of the channels that occur between the outer surfaces of the armature (Fig. 4), surface tension forces play an important role. In general, the surface of the armature can be wetted to varying degrees. In the ideal case, such a ratio of brands of reinforcement material is chosen that would be sufficiently wetted by the specified brand of binder. The length of penetration of the liquid phase into the capillary channels, in general, depends on the pushing pressure and the number of repeated loads [1, 6].

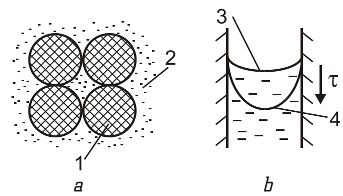

Fig. 4. Cross-section of the CM: *a* – transverse; *b* – longitudinal; 1 – armature; 2 – matrix; 3 – position of the liquid boundary; 4 – position of the matrix border during solidification

The simplest physical model of the occurrence of shrinkage stresses caused by surface tension forces was considered (Fig. 4). Threads of armatures located next to each other will form channels of complex shape and small size. When impregnation, they must be filled with a liquid compound. If they wet the surface of the fibers (for which special measures are taken), the border of the compound has a concave shape. Its chemical shrinkage occurs and its border increases in curvature in the process of hardening.

Excessive capillary pressure helps to spread the reinforcement fibers and reduce the density of their arrangement. But the main thing is that the reduction of the curvature radius of the distribution boundary during approval leads to the appearance of shrinkage stresses τ, which are added to temperature stresses.

After stopping the pulse action, the boundary of the liquid phase can go down (Fig. 4, *b*), but at static (relatively low) pressure, which is applied to the part during polymerization, the liquid phase will more easily fill the capillary channel to a greater length and solidify at a greater depth.

3.3. The formation mechanism of non-monolithicity during the formation of point joints M+CM. When forming integral panels or aggregates from CM, point joints of metal parts (formed bolts, nuts, washers and fittings) with the main part made of CM are used quite often (Fig. 5).

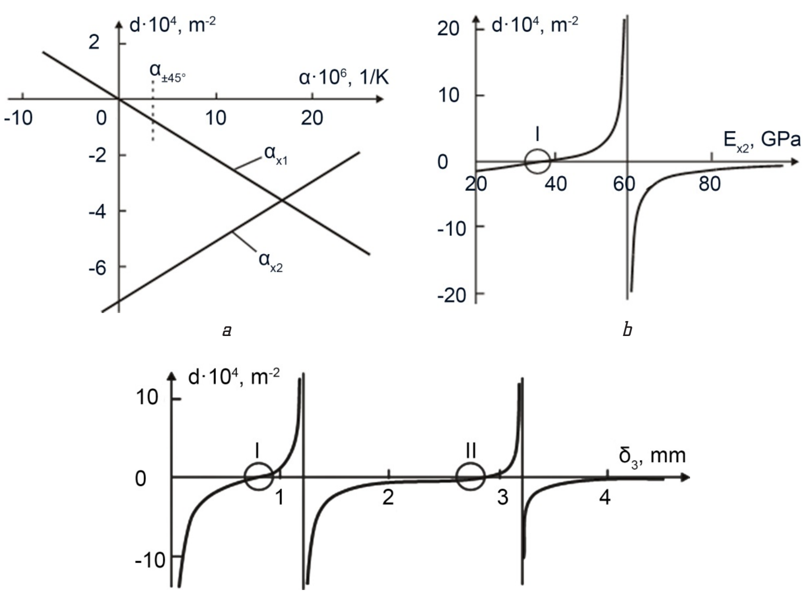

Fig. 3. Dependence of the second derivative on the twist angle of the profile *d* along the length of the profile: *a* – on the CLTE of parts 1 and 2; *b* – from the modulus of elasticity along the *x* axis of part 2; *c* – from the thickness of the lining 2; $\alpha_{\pm 45°}$ – CLTE of the lining package, which is reinforced at an angle of ±45°; I, II – regions with a sufficiently small twist angle

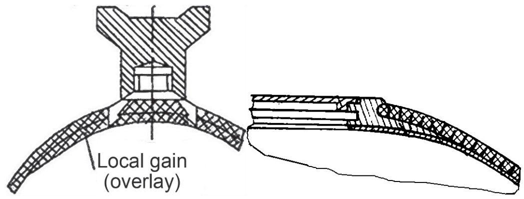

Fig. 5. Examples of folding units in which joints of the M+CM type are implemented

When local transversal microelements are introduced into the regular structure of the CM, it is disturbed in the form of non-monolithic zones (Fig. 6). These zones are filled with gas (or binder) and practically do not perceive the active load. It is possible to assume that reinforcement fibers will cross in the space between local elements. This generally leads to a noticeable loss of the load-bearing capacity of the connection. As can be seen from Fig. 6, *b*, the degree of violation of the regular structure with the non-oriented position of the passage channels for fibers is greater than with the linear arrangement of microelements.

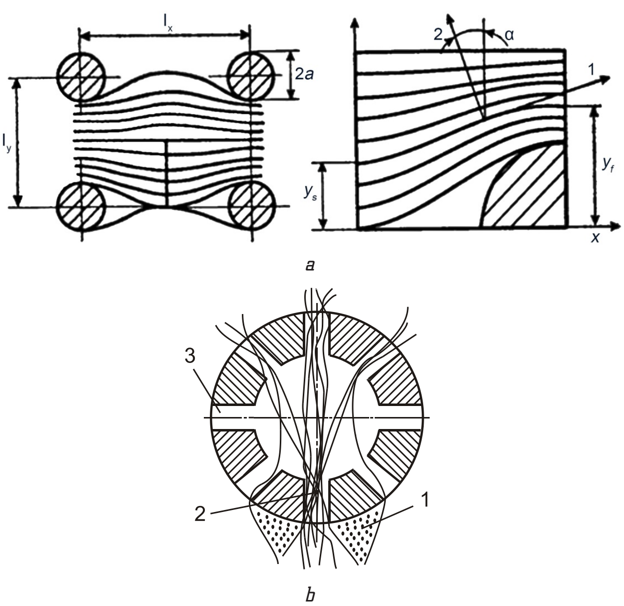

Fig. 6. Scheme of the arrangement of reinforcement fibers in irregular zones: *a* – when a row arrangement of fastening microelements; *b* – when installing local elements (bolts, nuts, etc.); 1 – reinforcement absence zone; 2 – fiber accumulation zone; 3 – unfiled zone

In order to partially fill such zones with fibers (due to their bending) or with a liquid phase, it is necessary to apply intense impulse pressure to them during molding.

To increase the infiltration degree, it is suggested to press the CM layers with shock waves. The effectiveness of the process was confirmed experimentally [7]. But a single impulse load contributes to the seepage completeness, but it is difficult to significantly reduce shrinkage stresses.

Significant relaxation of shrinkage stresses and residual stresses of a different nature can be facilitated by intense transmission through the reactive volume of stress waves generated during the polymerization reaction [1, 2, 8]. Due to the macro-continuity of the CM volume reacting with the wave, the direction of transmission of the compression waves, in the first approximation, can be chosen arbitrarily. A possible schematic diagram of the device for implementing this model is shown in Fig. 7.

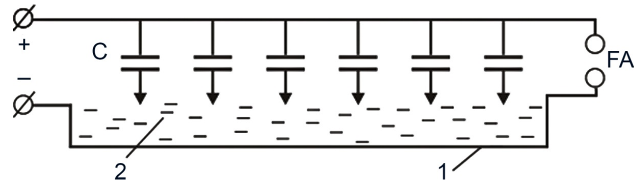

Fig. 7. Schematic diagram of the device for removing the residual stresses in profiled products from CM during polymerization: 1 – external elastic surface of the shape setting tool; 2 – operational interval; C – capacitor bank; FA – forming arrester

Devices for generating powerful compression waves, for example, using an electro-hydraulic discharge has long been known [8–10]. Multi-electrode generators of pressure waves allow controlling the frequency and intensity of the load with such waves in wide ranges.

The device works in the following way. When high voltage is applied, capacitor batteries are charged. After closing the arrester, which forms the field of discharges, electrohydraulic discharges occur at the discharge working intervals. The time of energy release in each of the intervals is controlled, and the load intensity is directly proportional to the square of the capacitor charging voltage. Thus, the forming tool surface is loaded with compressive pulse bursts that are transmitted to the reacting volume.

The intensity of the technological load on the object of processing is determined by the pressure on the tool surface, time and the radius vector of the point [10], and it should also be comparable to the level of residual stresses.

The limits and conditions of the applied solutions are determined by the dimensions of the available equipment, the complexity of the geometry of the connection structure, the strength and rigidity of its elements, and the features of the operating conditions of the product.

The prospect of further research is the development of practical recommendations for the designer (technologist) regarding the selection of geometric and physical-mechanical parameters of thin-walled composite profiles, taking into account strength limitations and limitations on minimum warping.

The conditions of martial law in Ukraine had a very negative impact on the conduct of scientific research, as their funding decreased sharply, strict restrictions on access to laboratories and equipment appeared, and many members of research groups were forced to leave or change their places of stay.

4. Conclusions

As a result of the conducted research, the calculation of the stress-strain state of thin-walled composite profiled parts shows that thermal stresses lead to the appearance of significant total twisting of the product. Chemical shrinkage and surface tension forces increase torsional deformations.

It is found that changing the reinforcement angle (which is different from 0°) of the profile with doubler on the angular profile and the number of monolayers in the profile with doubler allow to reduce the twisting angle of the profile.

It is established that the transmission of bundles of compression waves throughout the volume of the CM being polymerized can reduce residual stresses. The intensity of such influence is determined by the level of technological residual stresses arising in the product.

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Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Guz, A. N., Tomashevskii, V. T., Shulga, N. A., Iakovlev, V. S. (1982). *Tekhnologicheskie napriazheniia i deformatcii v kompozitcionnykh materialakh.* Kyiv: Vishcha shkola, 270.
2. Cappello, R., Pitarresi, G., Catalanotti, G. (2023). Thermoelastic Stress Analysis for composite laminates: A numerical investigation. *Composites Science and Technology, 241,* 110103. doi: https://doi.org/10.1016/j.compscitech.2023.110103
3. Kučera, P., Kondratiev, A., Píštěk, V., Taranenko, I., Nabokina, T., Kaplan, Z. (2023). Thin-walled open-profile composite beams under thermo-mechanical loading. *Composite Structures, 312,* 116844. doi: https://doi.org/10.1016/j.compstruct.2023.116844
4. Taranenko, I. M. (2003). Raschet deformirovannogo sostoianiia z-obraznogo kompozitnogo profilia. *Voprosy proektirovaniia i proizvodstva konstruktcii letatelnykh apparatov, 33 (2),* 67–73.
5. Belmas, I., Bilous, O., Tantsura, H. (2022). Determination of the stress-deformed state of a multilayer composite. *Strength of Materials and Theory of Structures, 109,* 426–440. doi: https://doi.org/10.32347/2410-2547.2022.109.426-440
6. Teixidó, H., Staal, J., Caglar, B., Michaud, V. (2022). Capillary Effects in Fiber Reinforced Polymer Composite Processing: A Review. *Frontiers in Materials, 9.* doi: https://doi.org/10.3389/fmats.2022.809226
7. Krivtcov, V. S., Gilmanov, E. S. (1998). Formovanie kompozitnykh konstruktcii impulsnym metodom. *Sovershenstvovanie protcessov i oborudovaniia obrabotki davleniem v metallurgii i mashinostroenii.* Kramatorsk, 268–272.
8. de Almeida, E., Hofland, B. (2020). Validation of pressure-impulse theory for standing wave impact loading on vertical hydraulic structures with short overhangs. *Coastal Engineering, 159,* 103702. doi: https://doi.org/10.1016/j.coastaleng.2020.103702
9. Gulyi, G. A. (1990). *Nauchnye osnovy razriadnoimpulsnykh tekhnologii.* Kyiv: Naukova dumka, 208.
10. Taranenko, M. E. (2011). *Elektrogidravlicheskaia shtampovka: teoriia, oborudovanie, tekhprotcessy.* Kharkiv: Natc. aerokosm. un-t im. N. E. Zhukovskogo «Khark. aviatc. in-t», 272.

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