МЕХАНИКА КОМПОЗИТОВ

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TENSILE FRACTURE SPECIFICITY OF UNIDIRECTIONAL METAL-POLYMER GLASS-FIBER COMPOSITES WITH CORD WIRE

In this paper, the problem of increasing the strength and elastic modulus of unidirectional structural glass-fiber-reinforced plastic (GFRP) is considered and the possibilities of using hybrid reinforcement based on GFRP and high-strength steel cord wire are discussed. Static tensile testing of laboratory samples of metal-glass-reinforced plastics was performed, the results of which show the significant dependence of the mechanical characteristics on the adhesion of both filler components to the binder. To realize high mechanical characteristics of the metal-glass-polymer composites under consideration, it is necessary, besides ensuring strong adhesion of filler to binder, to create a certain gradient of the elastic modulus of the intermediate layer near the surfaces of the components using bionic principles for constructing high-strength natural joints.

Keywords: *directionally reinforced composites, metal-glass plastics, hybrid fillers, glass-fiber-reinforced plastic, cord wire, mechanical tests, fracture, adhesion*

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Introduction. Increasing the strength and elastic modulus of structural plastic composites in construction, the automotive industry, implantology, and so on, by introducing a high-modulus reinforcing filler into the structure of the material is an important practical task. The most actively studied are unidirectional (UD) glass-carbon fiber-reinforced plastics, the mechanical characteristics of which have been studied in various volumetric ratios of glass and carbon fiber. The difference in the strain diagrams of these composites during the initial loading (when the elastic modulus is maximal) and in subsequent cycles (due to multiple breaks in the carbon fibers) shows that the modulus decreases to a certain stable value [1]. With a small (up to 10 wt.%) carbon fiber content, the value of the elastic modulus approximately corresponds to that found by the rule of mixtures [2]. The collective effect of hybrid reinforcement due to the redistribution of tensile stresses during the combined deformation of broken carbon fibers and preserving the continuity of glass fibers can increase the UD glass-fiber-reinforced plastics (GFRP) modulus (usually not exceeding 55 GPa) by 40–50 %. The effect of a hybrid reinforcement scheme on the mechanical characteristics of a UD composite was studied by [2–4]; they showed that the hardening efficiency depends not only on the properties and volume fraction of the carbon fiber but also on its location in the GFRP bar due to the "shear lag" effect.

Steel is an alternative to expensive carbon fiber in a hybrid filler, e. g. corrugated steel reinforcing bars with glass-reinforced plastic coating [5–7]. Obviously, they have other properties than glass-carbon fiber-reinforced plastics and have been designed to reduce weight and to ensure the corrosion resistance of the steel reinforcement rather than to increase the modulus of the GFRP. The production of such materials requires special equipment.

Unlike reinforcing bars, thin steel wire can be introduced into a GFRP bar along conventional lines for the production of composite reinforcement. The resulting materials are similar to carbon fiber reinforcement but have two features in addition to density, dielectric properties, etc. due to the fact that the diameter of the used steel wire is 1–2 orders of magnitude larger than that of filaments. Firstly, the contact area of the wire with the polymer matrix is significantly smaller than that of many carbon fibers. Therefore, the stresses in the adhesive contact of the wires and the polymer will be an order of magnitude higher than at the interface between the fibers and the polymer with an equal volume fraction of carbon and steel fillers. Thus, the role of the bond strength of the wire with the matrix increases substantially in the formation of the properties of the composite.

Secondly, the above collective effect is realized due to the presence of many thousands of high-modulus carbon filaments in the carbon reinforcement. Since metal-polymer reinforcement includes no more than several tens of wires, its properties are sensitive not only to the volumetric metal content but also to the number of wires.

Hybrid reinforcement with a volume fraction of steel of 40 % was studied in [8]; wires with a diameter of 1 mm were evenly distributed in a GFRP bar coated with thin layers of high-modulus organoplastic and carbon-reinforced plastic on the outside. The elastic modulus of the obtained composite material was 142 GPa and the tensile diagram had a bilinear shape typical for metal-glass-reinforced plastics with a decrease in the angle of inclination of the curve when the yield point of steel was reached.

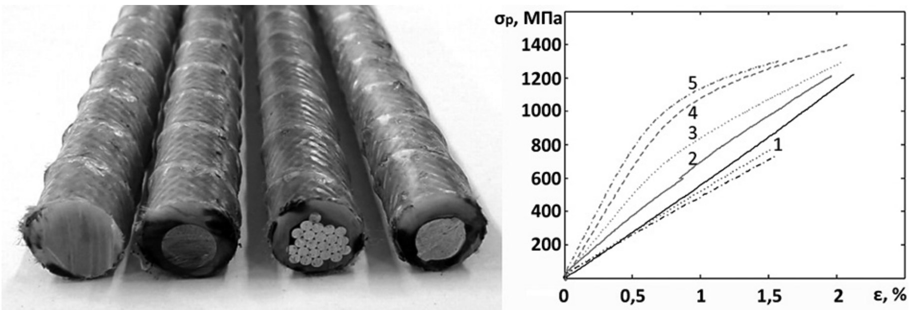
A comparison of the characteristics of metal-glass-reinforced plastic reinforcement containing steel bars of various diameters or a different number of wires with a diameter of 2 mm (Figure 1 *a*) was made by [9].

The outer layer of the reinforcing bar was made by braiding, which contributed to the consolidation of the metal-polymer composite. Even a relatively small addition of steel ensured an increase in the elastic modulus of the material from 50 to 77 GPa (curve 2), and the modulus reached 95 GPa (curve 3) with a volume fraction of the wire of around 30 %.

According to this characteristic, reinforcement with wire is not inferior to carbon-glass-reinforced plastic based on low- or medium-modulus carbon fibers. For example, fibers with an elastic modulus of 230 and 240 GPa were used in [2], which are classified as low-modulus according to standard GOST 57407. The advantage of a metal-polymer glass composite is the proximity of the coefficients of thermal expansion of steel and GFRP (along the fibers), while significant temperature stresses can arise in carbon-glass reinforced plastic due to the low coefficient of thermal expansion of the carbon fibers.

The level of operating stresses in composite bars is usually far from the ultimate strength of UD GFRP, and the allowable loads are limited by concrete deformations and stresses at the interface between the bars and the concrete. A composite with a relatively low volume fraction of steel is of the greatest practical interest. It provides a significant (50–75 %) increase in the elastic modulus while maintaining the advantages of GFRP reinforcement: corrosion resistance and transportability. It is advisable to use high-strength steel wire of small diameter with a protective coating to prevent corrosion.

The Belarusian Steel Works in Zhlobin produces RML bronze-plated bead steel wire for reinforcing high-pressure hoses. The wire has a diameter of 0.2 to 0.81 mm, strength of 2,500 MPa, and an elastic modulus of 200 GPa. The indicated value of the ultimate strength is explained by both a high carbon content in steel and cold-hardening with repeated thin drawing [10]. RML wire is not subject to creep and its elongation at break



a *b*

Figure 1 — Photograph of metal-glass-reinforced plastic bars (*a*) and tensile diagrams of GFRP and metal-glass-reinforced plastic bars (*b*) [9]: 1 — a GFRP bar with a diameter of 13 mm (the control); 2–5 — metal-glass-reinforced plastic bars of the same diameter with 4, 13, 23, and 29 wires and metal volume fractions of 9.8 %, 31.8 %, 57 %, and 70.3 %, respectively

does not exceed 2.6 % [11]. Therefore, the properties of metal-glass-reinforced plastic during prolonged and cyclic loads are preserved if there is a strong adhesive bond between the wire coating and the matrix polymer. Typically, a lubricant is present on the surface of the brass metal cord that increases adhesion to rubber [12] but prevents adhesion to the thermosetting resin. In this regard, wire with a polymer coating or finish that creates a chemical bond between the metal and the matrix is promising for the manufacture of metal-glass-reinforced plastics.

The combination of steel wire with thermosetting binders is relevant not only for the manufacture of structural reinforcement. Such a metal-polymer composite can be used in GFRP strength members for reinforcing and armoring fiber-optic cables, in automobile and ship structures, and UD steel cord tape for the external reinforcement of concrete structures [13]. Thus, studying the possibility of using cord wire to increase the elastic modulus of GFRP is an urgent task in the field of creating high-strength composites for various technical purposes.

The aim of work is to study the influence of the adhesion of the reinforcing filler to the binder on the mechanical properties and nature of the fracturing of the metal-polymer composites in the form of UD GFRP with RML wire under uniaxial tension.

Materials and research methods. Laboratory test specimens were made on the basis of manufactured glass rovings with a linear mass of 2,400 and 1,200 g/km, RML-2 steel wire with a diameter of 0.4 mm, and epoxy binders with different adhesion strengths to the specified reinforcing materials for an experimental assessment of the influence of the adhesion strengths of the components on the properties of metal-glass-reinforced plastic at JSC "Polotsk-Steklovolokno". Equipment was used for the manufacture of impregnated rovings according to the standard in [14]. The difference from the standard method was that the RML-2 wire was pre-stretched onto the winding frame along which the ES 17 2400 53S glass roving was laid, soaked in a binder in the bath, and passed through a die with a diameter of 1.4 mm. The roving was rolled onto the wire to ensure the maximal contact area (Figure 2). A number of samples were made using ES 16 1200 53S roving and passed through a die with a diameter of 1.1 mm. On the opposite side of the samples, a second impregnated roving was laid so as to completely cover the wire with GFRP. The volume fraction of steel in the samples was around 7.5 % in both cases. Control specimens of impregnated roving without wire were made via the standard method.

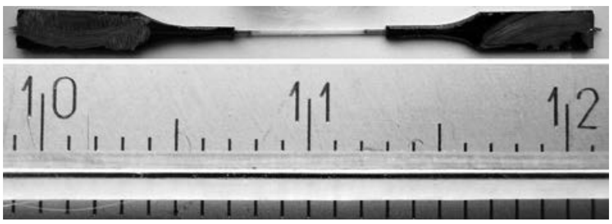


Figure 2 — A specimen based on RML-2 steel wire with a diameter of 0.4 mm and ES 17 2400 53S glass roving

After curing and holding for 2–3 days, test specimens were placed in silicone molds in which anchors were cast from the epoxy end sections for clamping in the grips of the testing machine. The length of the working section of the specimens was 80 mm. The mass fraction of the binder in the GFRP was determined in the laboratory of JSC "Polotsk-Steklovolokno" as around 30 % (excluding the wire).

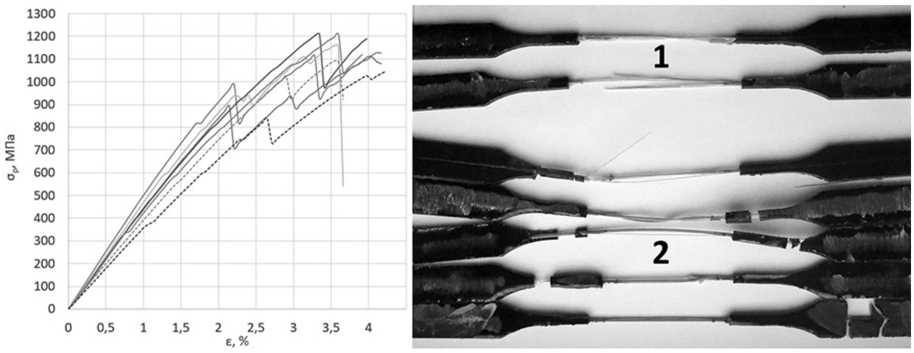
Binders based on epoxy-dian resin Eposir 7120 (similar in properties to resin ED-22) and hardeners of two types were used. The first was modified amine hardener ETAL-45M in the amount of 50 parts by weight per 100 parts of resin (phr). ETAL-45M provides a low viscosity of the composition, fast and complete capillary impregnation of the roving, a gelation time of more than 60 min, and smooth polymerization without a sharp exothermic peak [15]. This binder has a strong bond with the silane sizing of fiberglass, high elasticity, and crack resistance. To improve adhesion to metal, 0.5 phr of adhesion promoter BYK-4511 was added to the composition. This composition was also used to fill the anchors.

The second was 25 phr of Vestamin R-215 diamine hardener. Designed for the production of alkali-resistant reinforcement at 180–200 °C, this hardener is able to crosslink the epoxy resin at room temperature, although in this case, the process stops after reacting with primary amines [16]. The resulting polymer easily crumbles, and upon bending or torsion of the microplastic, the binder crumbles, which indicates a very low strength of its adhesion to the fiber. The rods using R-215 hardener were formed at room temperature and served to study the effect of adhesion on the nature of the fracturing of metal-glass-reinforced plastic in comparison with the samples of the first series.

Mechanical testing for static tension at loading rate of 5 mm/min was carried out with a universal machine Instron 5567 (V.A. Belyi Metal-Polymer Research Institute of the NAS of Belarus) taking into account the guidelines for the certification of the stress-strain properties of directionally reinforced composites described in [17–20]. Tested separately with a Zwick 2.5 kN machine, RML-2 wire showed an elastic modulus of 200 GPa and a breaking force of around 330 N, which corresponds to the certified value. The elastic modulus of the samples was determined in the range of elongation of 0.3–1.5 %, where the dependence of the tensile strength (elastic modulus) ($\sigma_p(\varepsilon)$) is close to linear. A comparison was made of the indicators obtained by measuring the elongation of the sample using an extensometer and by moving the crosshead of the machine. This methodological test confirmed the conclusions about the need to use an extensometer to accurately determine the relative elongation [11]. Consequently, the elastic modulus of the composites, the value of which when calculated from the crosshead movements, were underestimated by almost 1.5 times.

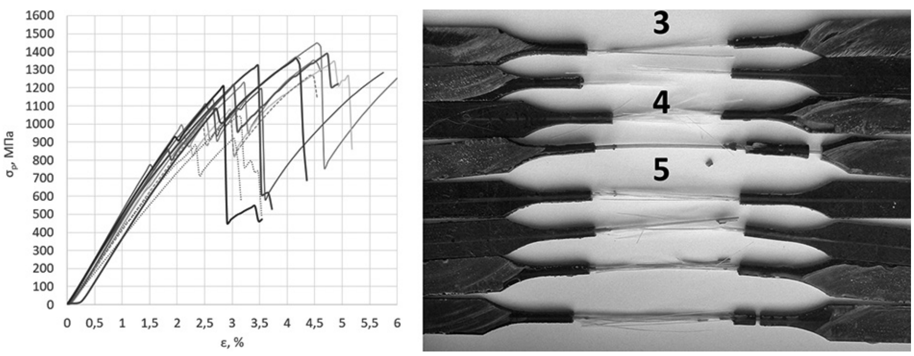
Results and discussion. The calculation of the characteristics of the metal-polymer composites according to the rule of mixtures was carried out under the following conditions. The densities and elastic modulus values of fiberglass, binder, and wire were 2.55, 1.2, and 7.8 g/cm^3 and 70, 5, and 200 GPa, respectively. The volume fractions of the fiber and binder in the glass composite were 55 % and 45 %, respectively. The calculated binder mass fraction (28 %) approximately corresponded to that obtained during the annealing of the specimens. Taking into consideration the indicated diameter of the die, which determined the cross-sectional area of the rods as 1.54 mm^2, the theoretical value of the elastic modulus of the glass-reinforced plastic bar was 40.8 GPa, and the introduction of cord wire with a diameter of 0.4 mm increased it to 52.8 GPa (i. e. by 29 %). It was expected that the metal-glass-reinforced plastic would show an elastic modulus in the order of 200 GPa at the beginning of initially applying the tension. However, a thin but very rigid RML wire breaks with a force of more than 330 N, and the angle of inclination of the diagram decreases suddenly to a value corresponding to the 40 GPa GFRP modulus.

The experimental data presented in Figures 3–6 and Table show that none of the samples was destroyed in this idealized scenario. The actual scene corresponds to a complex combined deformation of a metal-glass-reinforced plastic bar and polymer anchors. It is accompanied by the loss of the adhesive bond between the GFRP and the wire, which gradually stretches out from the anchors under tension that sometimes leads to their breaking. The results also demonstrate the strong



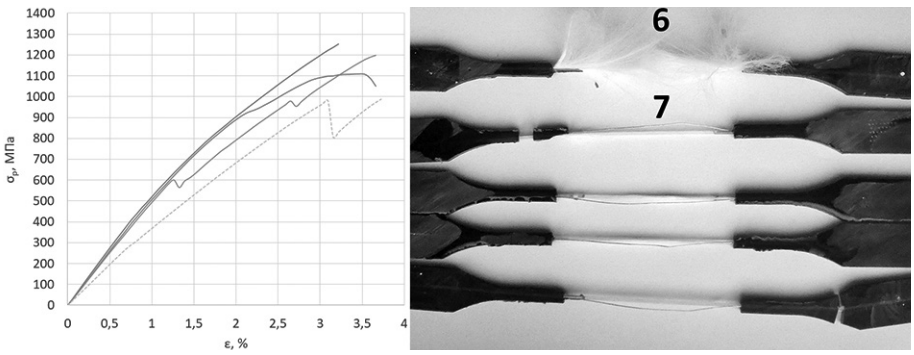
a *b*

Figure 3 — Strain diagrams (*a*) and a photograph (*b*) of the fractured series 1 (dashed lines) and 2 (solid lines) composites



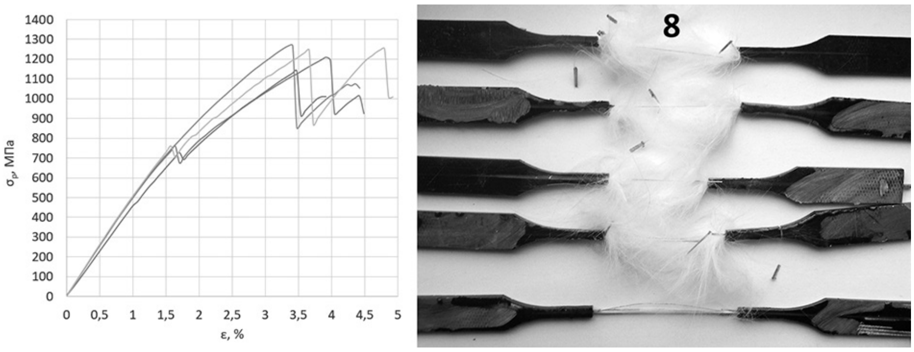
a *b*

Figure 4 — Strain diagrams (*a*) and a photograph (*b*) of the fractured series 3 (dotted lines) and 4, 5 (solid lines) composites



a *b*

Figure 5 — Strain diagrams (*a*) and a photograph (*b*) of the fractured series 6 (dotted line) and 7 (solid lines) composites



a *b*

Figure 6 — Strain diagrams (*a*) and a photograph (*b*) of the fractured series 8 composites

Table — Material composition and test results of composite specimens

Series No.	Material Composition	Number of Samples	Fracture Nature	Average Values	
				E_p (GPa)	σ_p (MPa)
1	1 ES17 2400 53S roving; binder with 45M hardener	2	Multiple longitudinal delaminations of the working part of the rod and fan-shaped separation of the fibers (“brooming”).	34.7	1,068
2	1 ES17 2400 53S roving; RML-2 wire (0.4 mm); binder with 45M hardener	5	The working part of the sample was without damage. Anchor fracturing. Rod deformation and elongation. Separation of steel wire from GFRP.	42.4	1,159
3	2 ES16 1200 52S rovings; binder with 45M hardener	2	Similar to series 1. Fragmentation of the sample rod into a large number of fibers with the formation of a “broom”.	42.8	1,271
4	2 ES16 1200 52S rovings; RML-2 wire (0.4 mm); binder with 45M hardener	5	Splitting of the rod with the formation of a broom. Preservation of the continuity of the wire of one sample, 1 case of a wire break in the anchor of the sample, 1 case of a wire break in the working section of the sample. Anchor fracturing.	47.0	1,362
5	2 ES16 1200 52S rovings; RML-2 wire (0.4 mm); binder with 45M hardener and BYK-4511promoter	4	Splitting with the formation of a “broom”. The wire of one sample was not destroyed. The third sample was destroyed in the working area. Anchor fracturing.	46.8	1,320
6	1 ES17 2400 53S roving; binder with R215 hardener	1	Swelling of the filaments with complete loss of the binder and formation of glass wool.	33.6	988
7	1 ES17 2400 53S roving; RML-2 wire (0.4 mm); binder with R215 hardener	3	Detachment of the wire in the work area with its pronounced elongation in the absence of rupturing of the rods. Anchor fracturing.	45.1	1,187
8	2 ES16 1200 52S rovings; RML-2 wire (0.4 mm); binder with R215 hardener	4	Fluffing of filaments and wire breaking in all samples after fracturing of the rod. Anchor fracturing.	45.6	1,217

Note: E_p — modulus of elasticity; σ_p — tensile strength.

influence of the adhesion strength of the components on the fracture pattern of the composite, reflecting the importance of the role of the interface between the binder and the filler.

Analysis of the results revealed the following features of strain and fracture of samples under uniaxial tension. First, upon fracturing, fiber composites with strong adhesion of the fiber and the binder (series 1 and 3 samples) exhibited specific longitudinal delamination of the glass-reinforced plastic bar with the formation of a “broom”. Low adhesion of the binder to the fiber (series 6) led to delamination of the external filaments in the process of stretching and fluffing of the fibers upon fracturing of the bar, thereby causing a decrease in the ultimate strength and elastic modulus.

Secondly, for samples with a wire located on the outside of the bar (series 2 and 7), the wire exfoliated during tension regardless of the initial bond strength with the polymer matrix. The test stop for these samples was associated with the fracture of the anchors rather than rupturing of the wire or bar. A wire having a weak adhesive bond with GFRP is drawn from the anchors, thus the average shear strength of the connection of the wire and the epoxy binder at the anchor section did not exceed 3–5 MPa, even when taking into account the known factor of the concentration of shear stresses [21].

Thirdly, the ultimate force for a given wire of 330 N was achieved with a relative elongation of the samples of around 0.5 %. Only the bars in which the wire was completely coated with glass-reinforced plastic (series 4, 5, and 8) showed wire breaking in the working section. However, it is probable that fracturing of the wire and GFRP occurred simultaneously when the wire suddenly suffered the maximum load of more than 1500 N. Specimens of metal-glass-reinforced plastic with strong adhesion of components (series 4 and 5) showed higher mechanical characteristics than ones with weak adhesion (series 8). However, the tensile modulus did not reach the calculated value during stretching, although it did exceed the GFRP modulus by 15–20 %. This indicates preservation of the integrity of the wire due to insufficient adhesion to the matrix.

Fourthly, the effect of the BYK-4511 additive on increasing the adhesive strength of the epoxy binder in these experiments was not elucidated. Lastly, to improve the testing technique of the investigated high-strength composites in tension, it is necessary to increase the strength of the specimen anchors.

To realize high strength of the composites under consideration, it is necessary to create a certain gradient of the elastic characteristics of the intermediate layer near the surfaces of the components, including the use of bionic principles for constructing high-strength joints [22] (e. g. by nanomodification of the intermediate layer [23]).

On the other hand, metal-polymer composites with low bond strength of the reinforcing components can be effective energy-absorbing materials that may be the topic of perspective studying.

Conclusions. The possibility of using cord wire to increase the strength and elastic modulus of unidirectional glass-carbon fiber-reinforced plastics was shown. The study the influence of the adhesion of the reinforcing filler to the binder on the mechanical properties and nature of the fracturing of these metal-polymer composites under uniaxial tension is performed.

To realize high strength and elastic modulus of UD GFRP, it is necessary to (i) ensure high adhesion of the binder to the wire, (ii) optimize the structure of the metal-polymer glass-fiber composite, and (iii) create a certain gradient of the elastic characteristics of the intermediate layer between reinforcing and matrix components.

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СПЕЦИФИКА РАЗРУШЕНИЯ ПРИ РАСТЯЖЕНИИ ОДНОНАПРАВЛЕННЫХ МЕТАЛЛОПОЛИМЕРНЫХ СТЕКЛОКОМПОЗИТОВ С КОРДОВОЙ ПРОВОЛОКОЙ

В статье рассмотрена проблема повышения прочности и модуля упругости однонаправленных конструкционных стеклопластиков. Показаны возможности использования гибридного армирования на основе стекловолокон и высокопрочной стальной кордовой проволоки. Проведены испытания на статическое растяжение лабораторных образцов металлостеклопластиков, показавшие существенную зависимость механических характеристик и характера разрушения от адгезионной прочности соединения компонентов гибридного наполнителя со связующим. Для реализации высоких механических характеристик рассматриваемых металло-стекло-полимерных композитов следует, помимо обеспечения сильной адгезии наполнителя к связующему, создать определенный градиент модуля упругости промежуточного слоя вблизи границ раздела компонентов, используя бионические принципы конструирования прочных природных соединений.

Ключевые слова: *направленно-армированные композиты, металлостеклопластики, гибридные наполнители, волокнистые стеклопластики, кордовая проволока, механические испытания, разрушение, адгезия*

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