

Polymer Composite Materials: Technologies and Applications

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Abstract—The physicomechanical properties of polymer composites based on aramide fibers that are obtained by the wet-spinning technique with the use of epoxy binders are discussed. The chemical structures of reinforcing fibers and components of epoxy binders; the microstructures, surface structures, and some properties of aramide fibers; and the processes of manufacturing high-strength reinforced composites on their basis are described. Some product samples made of these composites are presented. The investigated reinforcing materials possess high tensile strengths and tensile moduli, which make it possible to obtain products with a high level of operational characteristics on their basis.

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INTRODUCTION

The development of composite materials with properties that are practically unattainable for conventional engineering materials, such as aluminum and titanium alloys and steels, has considerably contributed to decreases in weight and material consumption of products and to improvement in their reliability levels and operational lives.

Polymer composite materials (PCMs) possess a valuable complex of properties, the most important being low density and the related high specific strength and specific stiffness; corrosive resistance; the ability to withstand prolonged static and dynamic stresses; and the ability to operate in a wide temperature range, under alternating stresses, and in high humidity.

Polymer composites based on high-strength organic (aramide) and carbon-fiber fillers in a polymer matrix, that is, organic-fiber-reinforced plastics and carbon-fiber-reinforced plastics, are the most promising for use as engineering materials. Currently, organic-fiber-reinforced plastics based on aramide fibers have the highest specific strength among these materials. (In these cases, when increased stiffness of

the materials is required, carbon-fiber-reinforced plastics are applied.)

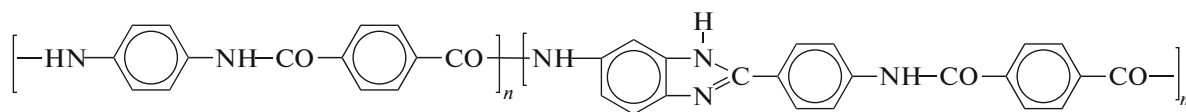
The development and production of aramide fibers are among the most outstanding achievements of polymer chemistry and technology of the 20th century. These fibers not only are unique in their mechanical properties, exceeding those of glass fibers and alloy steels, but also offer exciting possibilities for the modification and design of composite materials with properties predefined in accordance with engineers' requirements.

REINFORCING ARAMIDE FIBERS

Currently, two types of aramide fibers are most commonly used.

The first type is based on poly(*p*-phenyleneterephthalamide) (PPTA) and represented by the foreign fibers Kevlar® and Twaron® and the Russian fiber SVM.

The second type includes fibers based on heterocyclic poly(*p*-amides) and the copolymers close to them in composition. These are the Russian fibers Armos, Ruslan, and Rusar, which are based on polyamido-benzimidazole (PABI):



The properties of the fibers substantially depend on block ratio $n : m$.

The properties of aramide fibers have been much studied [1–5]. Aramides are rigid-chain polymers.

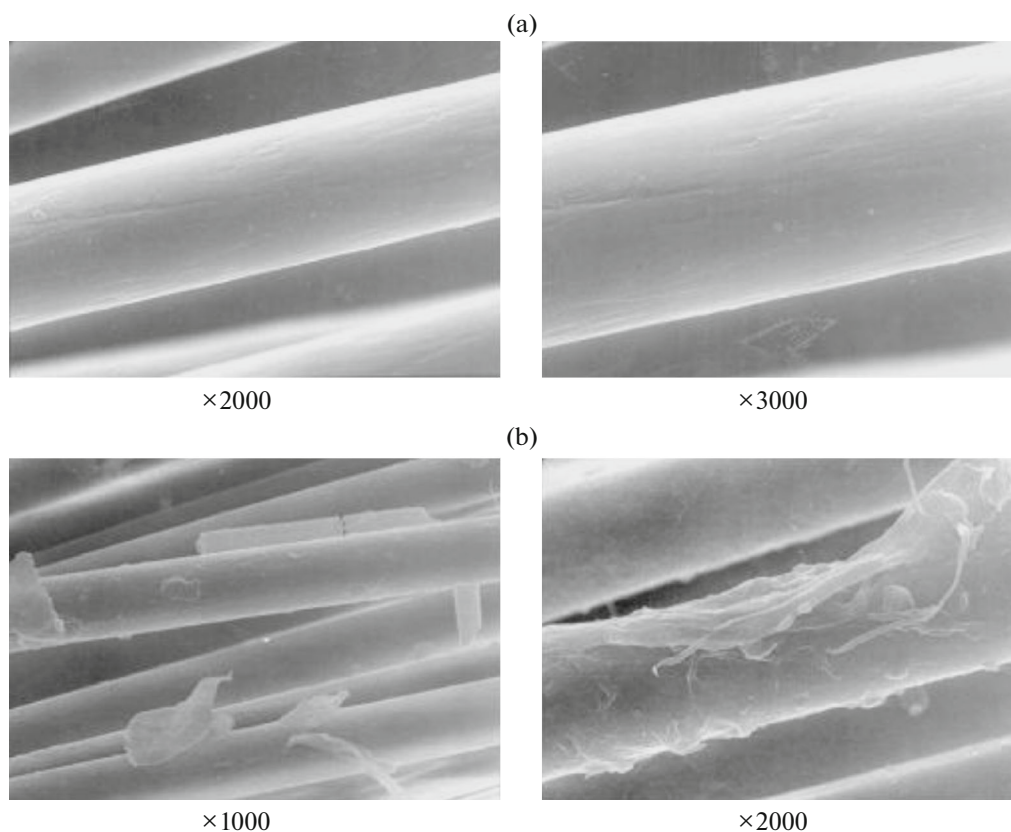


Fig. 1. SEM micrographs of surfaces of (a) Rusar-S and (b) Armos fibers.

The chemical structure of PABI molecules is irregular; therefore, the creation of a three-dimensional ordered network in PABI is impossible. However, the amorphous structure of this polymer does not prevent the occurrence of macromolecular orientation processes and the attainment of high stress–strain characteristics of fibers.

A high degree of orientation and a heterocyclic structure of aramide fibers provide a high degree of anisotropy of their characteristics. So far, many attempts to modify aramide fibers to form chemical crosslinks and increase strength performance in the transverse direction have failed.

Aramide fibers are characterized by high thermal stability and heat resistance; they are flame retardant and possess good dielectric properties and high stability against various environmental factors, such as the atmosphere, radiation, moisture, many types of chemicals, oil products, and microorganisms.

Until recently, the Armos fiber was the strongest aramide fiber [6, 7]. The reinforcing filler Rusar-S is a promising material for the preparation of high-strength polymer composites [8]. In terms of the chemical composition and technological parameters of synthesis, the Rusar-S fiber is similar to the Armos fiber. These fibers are formed from a polymer solution obtained by the low-temperature copolycondensation

of diaminobenzimidazole and *p*-phenylenediamine taken at different ratios in aprotic solvent.

The main difference between Armos and Rusar-S fibers, along with the ratio of two aromatic diamine units in polymer macromolecules, refers to the engineering parameters of the process of fiber spinning from polymer solutions: namely, different polymer concentrations; different compositions and acidities of spinning baths; and different methods of the spinning process, namely, the “wet” method for Armos and the “dry–wet” method for Rusar-S.

When the wet process is used, the polymer-solution jet appears directly in the spinning bath after the die, while in the “dry–wet” process, the fiber goes through a “steam–air” layer. This circumstance substantially affects the properties of the spun fibers.

The fine details of the structural and morphological organization of Armos and Rusar-S fibers are revealed in electron micrographs of their surfaces.

Rusar-S fibers (Fig. 1a) obtained by the dry–wet method are smoother and more uniform and have less surface defects. A small amount of 0.5- to 1.0- μm polymer particles stuck to the fiber are seen.

As to Armos fibers (Fig. 1b) obtained by the wet method, the amounts of stuck extraneous particles are much higher; moreover, there is nonuniformity in

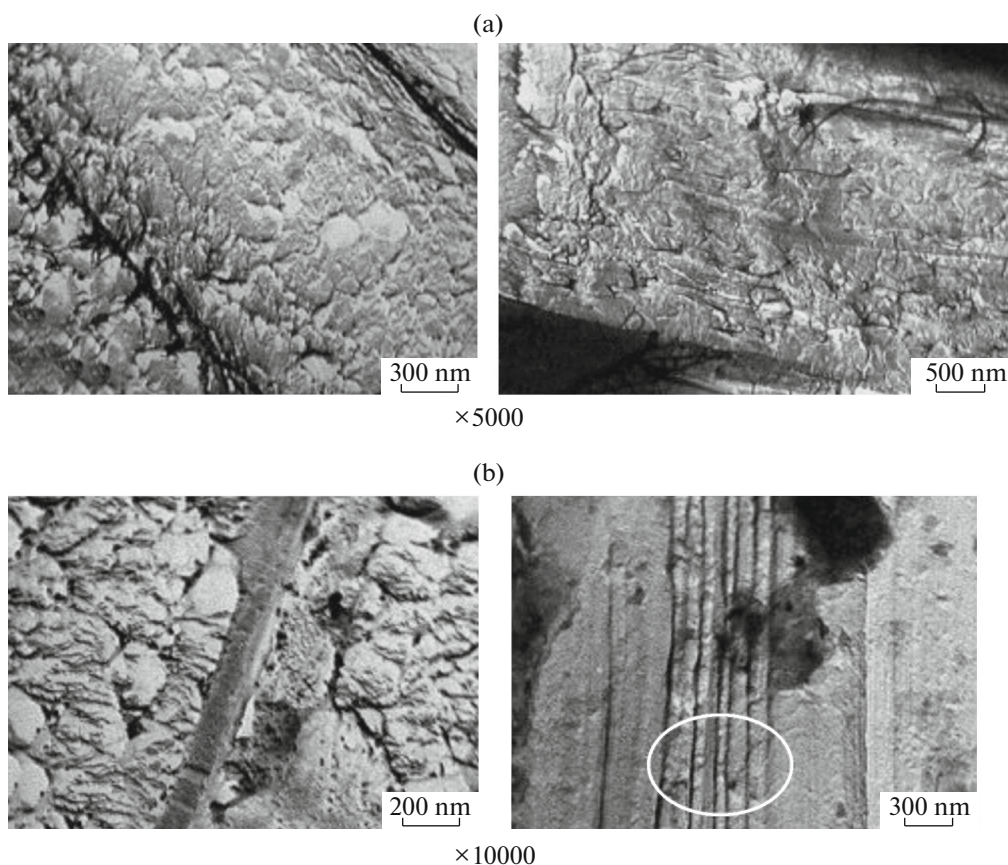


Fig. 2. TEM micrographs of the surface microstructures of (a) Rusar-S and (b) Armos fibers. In the region marked with an ellipse, the internal structure of a fibril is seen.

diameter along the fiber length as well as chip, hole, and seizing defects of fibers.

During the production process of wet spinning of Armos fibers, some of them are often broken in the spinning die (having about 300 openings). As a result, the number of elementary fibers in thread yarns formed after the die is less than nominal (the number of openings) and inconstant; that is, the Armos thread yarn is nonuniform in the number of constituting fibers and in their length; hence, its linear density and strength change along the thread.

These specific features cause differences in the physicochemical and physicomachanical characteristics of the elementary fibers, thread yarns, and thrown tows. Ultimately, this leads to higher physicomachanical parameters of organic-fiber-reinforced plastics based on Rusar-S fibers than those of composites based on Armos fibers.

Typical micrographs illustrating the structural and morphological organization of fibers are presented in Fig. 2. Both types of fibers contain two kinds of supra-molecular structures (lamellar and microfibrillar) and differ in the concentration of these structures and their mutual arrangement.

For example, in the Rusar-S fiber (Fig. 2a), lamellar structures are present to a higher extent, whereas fibrils are engrained between them; that is, the fiber has a lamellar-fibrillar structure. The average size of microfibrils is 100–150 nm; the thickness of lamellas is on the same order.

For Armos fibers (Fig. 2b), a predominantly fibrillar structural organization is observed. In addition, separate microfibrils arranged between macrofibrils that consist of lamellar structures arranged perpendicularly to the orientation axis occur in the fiber bulk.

Figure 3 shows pictures of the structures of microplastics based on Armos fibers and an epoxy binder; the pictures were taken after plasma etching. There are fibrous structures 0.2–0.5 μm in size that are identical in both directions, across and along the fiber.

The characteristics of the Russian aramide fibers are listed in Table 1. At present, the third-generation Rusar-S fibers have the highest physicomachanical characteristics of aramide fibers. Yarns based on these fibers are used in the production of composite materials intended for the production of heavily loaded special-purpose products with service lives from 15 to 20 years, depending on operational conditions.

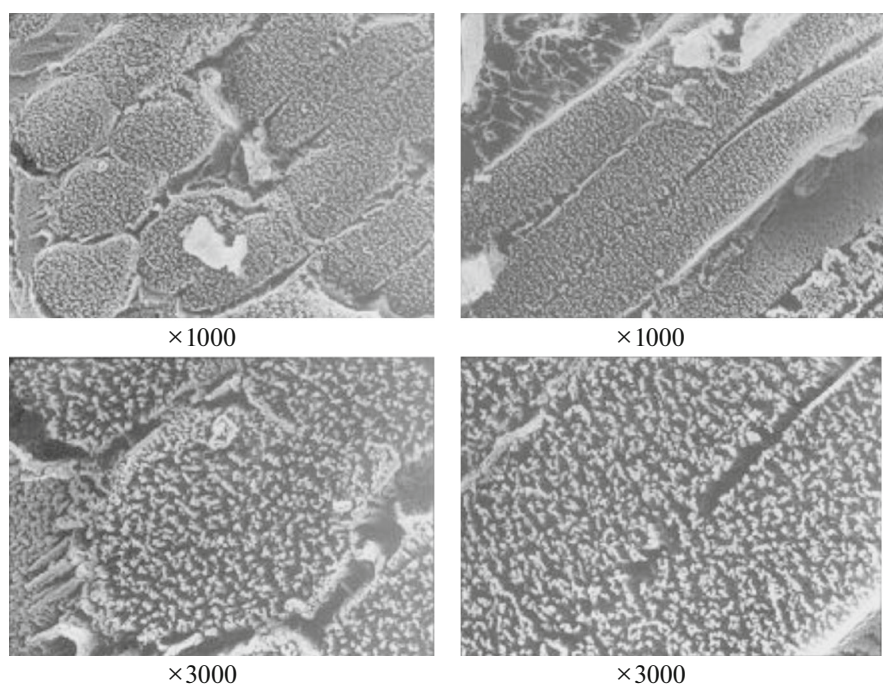


Fig. 3. Electron micrographs of the structures of microplastics based on the Armos fiber. On the left, the direct position of the fiber; on the right, the side position of fibers.

The use of the novel halogen-containing monomer MD for the synthesis of fiber-forming polymers made it possible to obtain a number of promising aramide yarns (Rusar-NT_m and Rusar-NT_s) with widely varying diamine ratios. As a result, the physicochemical properties and performance of the yarns obtained from these polymers may be varied over a wide range.

On the basis of Rusar-NT_s yarns with tensile moduli above 180 GPa, a microplastic with a strength of up to 6 GPa was obtained. Moreover, Rusar-NT_s yarns

have an increased (above 40%) oxygen index. They are neutral without any special thermal treatment, a feature that is very important, for example, for their applications in the aeronautical engineering.

Multiyear operational experience with aramide fibers shows that their initial physicochemical characteristics may be substantially increased (by more than 50%) via adjustment and optimization of their production parameters and stabilization of feedstock properties. It is expected that the organization of the serial production of Rusar-NT_s yarns will make it pos-

Table 1. Primary physicochemical characteristics of aramide fibers

Fiber	Density, g/cm ³	Tensile strength, GPa	Tensile modulus, GPa	Elongation at break, %	Moisture uptake under standard conditions, %	Service temperature (ultimate temperature), °C	Decomposition temperature, °C	Oxygen index, %
SVM	1.45–1.46	3.5–4.5	130–160	2.5–3.0	3.5–4.5	250–270 (300–330)	450–500	40–43
Armos, (Rusar, Ruslan)	1.45–1.46	4.5–5.5	140–160	3.0–3.5	3.0–5.5	250–270 (300–330)	450–500	39–42
Rusar-S	1.45–1.46	5.5–6.5	140–165	2.5–3.0	3.0–4.0	250–270 (300–330)	450–500	28–30
Rusar-NT	1.45–1.46	5.0–5.5	150–170	2.5–3.0	3.0–4.0	250–270 (300–330)	450–500	40
Terlon (Kevlar® analog)	1.45–1.47	3.5–4.5	140–150	2.5–3.0	2.0–3.0	200–250 (250–270)	420–480	28–30

Table 2. Properties of some epoxy binders

Binder	Processing temperature, °C	Temperature, °C; time of gelation, min	Strength, MPa		Relative elongation at break, %	Martens yield temperature, °C	T_g , °C (in contact with the Armos yarn)
			flexural	tensile			
EDT-10 (ED-20, DEG-1, TEAT-1)	65 ± 5	170; 13	70	48	3.5	105	75
EKhD-MK (EKhD, MTHPA, SKN-20)	50 ± 5	150; 8	80	50	3.0	165	92
EKhD-MD (EKhD, MTHPA, DEG-1, CO-3)	50 ± 5	150; 10	75	45	2.5	155	90
EN-I (UP-643, MTHPA, Alkofen)	50 ± 5	150; 6	78	46	2.0	165	95

EKhD is the polyglycidyl derivative of 3,3'-dichloro-4,4'-diamino-diphenylmethane; UP-643 is the epoxy-novolac resin; ED-20 is diglycidyl ether of diphenylol propane; DEG-1 is diglycidyl ether of diethylene glycol; MTHPA is *iso*-methyltetrahydrophthalic anhydride; TEAT-1 (triethanolamine titanate) is a mixture of two products, 1-(*n*-butoxy)-triethanolamine titanate and 1-(bis(2-oxyethyl)-1-aminoethoxy)triethanolamine titanate; CO-3 is the stabilizer (bis[3,5-di-*tert*-butyl-4-hydroxyphenyl]propyl)sulfide); SKN-20 is the SKN-20KTRA rubber, i.e., the copolymer of butadiene and acrylonitrile with end carboxylic groups; and Alkofen is UP-606/2, i.e., 2,4,6-tris(dimethylaminomethyl)phenol.

sible to increase their tensile moduli up to 200 GPa and that a strength of the microplactic above 7.5 GPa will be attained.

EPOXY BINDERS (MATRIXES) FOR POLYMER COMPOSITE MATERIALS

Properties of polymer composite materials are determined not only by the characteristics of the reinforcing filler but also by the nature and properties of the matrix (binder).

The nature of the matrix determines the level of operational temperatures of a composite, the character of changes in its properties during temperature and atmospheric effects, and engineering approaches to and regimes of preparing and processing materials into workpieces. Therefore, there are several special requirements on the polymer binder: thermal stability, chemical resistance, inflammability, minimized gas evolution, etc.

Composites based on the epoxy–diane resin (oligomer) ED-20 (the EDT-10 binder) and multifunctional resins (oligomers), including the EKhD epoxy resin (binders with the trademarks EKh-MK and EKhD-MD) and the UP-643 epoxy-novolac resin (the EN-I binder), are widely used to prepare engineering organic-fiber-reinforced plastics by the so-called “wet”-winding technique. (The wet-winding method involves impregnation of a fibrous reinforcing filler with a liquid binder containing no highly volatile solvents followed by placement of the impregnated material along the programmed directions onto a rotating mandrel and polymerization (setting) of the binder usually via heating in thermal ovens.)

The main properties of epoxy binders used to produce workpieces from PCMs based on the epoxy binders are summarized in Table 2.

ENGINEERING PARAMETERS OF THE PREPARATION OF ARAMIDE POLYMER COMPOSITES (ORGANIC-FIBER-REINFORCED PLASTICS)

The formation of composite materials begins with the application of the binder on the fiber surface. This stage is accompanied by several physicochemical processes that occur on the surface and determine to a considerable extent the mechanical properties of the composite materials. Such processes include wetting, adsorption, and adhesion of a liquid binder to the fiber.

The occurrence of the indicated processes in organic-fiber-reinforced plastics is complicated by the fact that fiber-swelling processes may proceed actively during the formation of composite materials owing to the diffusion of low-molecular-mass components of liquid binders into the fiber interior. As a consequence, the morphologies of fibers and their strength characteristics may change.

The kinetic parameters of these processes noticeably depend on both the chemical composition of an epoxy binder and the nature of an aramide fiber and the state of its surface.

The Winding-Tension Effect

The degree of implementation of the initial properties of reinforcing fibers in a composite material largely depends on engineering factors controlling the structures and properties of composites.

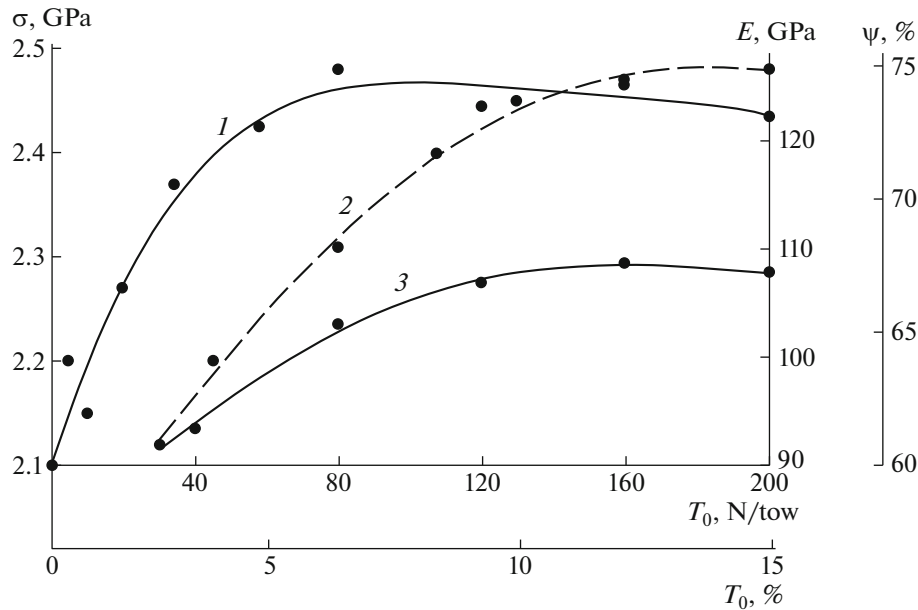


Fig. 4. The winding-tension effect on (1) strength σ , (2) elastic modulus E , and (3) reinforcement ratio ψ of a unidirectional organic-fiber-reinforced plastic samples with a diameter of 145 mm based on the Armos tow.

One of the engineering parameters that markedly affects the strength and elastic properties of the composite is the winding tension of the reinforcing material.

With an increase in tension to a certain limit, first, additional orientation of elements of the reinforcing material (fibers, yarns) along the placement direction occurs together with a decrease in the difference between lengths of constituent yarns in tows and the hereto-related increases in strength and stiffness properties of PCM. Second, an increase in tension increases friction forces on the working elements of yarn guide circuits causes a change in the strength of the reinforcing filler owing to its mechanical damage. Third, during winding of the reinforcing filler in the form of an engineering tape onto the curved surface of the mandrel, contact pressure N_0 of the engineering tape on the curved surface of the mandrel arises: It is determined from the ratio

$$N_0 = T_0 / \rho H_t,$$

where T_0 is the tension of the engineering tape, ρ is the mandrel curvature radius along the winding trajectory, and H_t is the width of the engineering tape.

The experimental data illustrating the tension effect on the properties of a unidirectional organic-fiber-reinforced plastic based on the Armos tow are presented in Fig. 4. It is seen that the strength reaches almost the maximum value, beginning from a tension of 70 N/tow (5.5–6.5% P_b), and remains constant up to a tension of 160 N/tow (10.5–12.0% P_b). The elastic modulus increases more smoothly, and, starting from a tension of 110 N/tow, its growth slows, while the ten-

duency to increase is preserved. The reinforcement ratio grows from 61 vol % at a tension of 30 N/tow to 75 vol % at a tension of 160 N/tow. Values of elastic modulus close to the limiting values are attained at tensions from 105 to 120 N/tow. In this case, the increase in the reinforcement ratio is proportional to the elastic-modulus increment.

Thus, the minimum necessary tension during winding of ring samples of organic-fiber-reinforced plastics based on the medium-strength Armos tow is 105 N/tow (approximately 8% of tow breaking load P_b).

To experimentally estimate the tow tension effect on the strength of microplastics and unidirectional organic-fiber-reinforced plastics in the case of a high-strength tow, the Ruser-S tow with a strength above 5000 MPa in the tow microplastic was used.

The tow tension in the microplastic winding was varied from 50 to 200 N/tow (from ~3 to 15% of the breaking load).

The obtained dependence of the strength of microplastics on the tow winding tension showed that changes in the winding tension of the high-strength tow within a wide range has almost no effect on the tow-microplastic strength. This finding may be explained by the fact that a high degree of orientation drawing is used in the process of preparation of the high-strength tow, being responsible to a significant extent for its high strength. Consequently, an increase in the winding tension of microplastics causes neither additional orientation nor marked changes in the interfiber space.

Table 3. Strength values of samples of ring unidirectional organic-fiber-reinforced plastics with different binders at various winding tensions

Binder	Reinforcement ratio, wt % (vol %)	Strength	Modulus
EDT-10	71(67)/77(73)	2790/2570	104/106
EKhD-MK	71(67)/76(72)	2780/2490	107/110

To ascertain the effect of high-strength tow tension on the strength of the unidirectional organic-fiber-reinforced plastic, unidirectional ring samples were prepared from the Ruser-S tow with the use of two brands of fillers, EDT-10 and EKhD-MK, with different tow winding tensions, namely, 50–60 and 100–110 N/tow.

The results of sample testing at a temperature of 20°C (Table 3) showed that the reinforcement ratio rises from 71–72 to 76–77 wt % (from 67 to 73 vol %), while the strength of organic-fiber-reinforced plastics drops by 8–12% for both brands of filler as the tension is increased from 50 to 100 N/tow. The moduli of organic-fiber-reinforced plastics decrease as well, albeit to a lower extent, by 3–6%. This finding may be explained by the increasing damageability of the tow on the winding-machine circuit with the increase in tension.

The properties of polymer composite materials largely depend on the ratio of the main components, that is, the binder and filler. The necessary and sufficient content of the binder is determined by the inter-fiber space of the organic fiber-reinforced plastic. The binder should be introduced in an amount that is necessary to fill the whole interfiber space to exclude to the maximum possible extent the possibility of pore formation and to provide integrity to the material.

The interfiber-space volume mostly depends on the contact pressure during winding, that is, ultimately, on the tension of the reinforcing filler, the workpiece geometry, the textile structure of the filler (the twisting and linear densities of yarns and tows) and the winding accuracy (the presence of clearances between tapes). In this case, the minimum deposition of the binder is provided by the use of untwisted or flat reinforcing fillers, accurate winding (without clearances), and the maximum contact pressure.

An increase in the contact pressure is usually accompanied by a change in the structure of a reinforced plastic: an increase in the fiber content, decreases in the contents of the binder and pores, and a decrease in the degree of inhomogeneity of the plastic-component distribution over the wall thickness of the workpiece during winding.

The results of investigations aimed at determination of the binder-content effect and the hereto-related reinforcement ratio on the strength properties of organic-fiber-reinforced plastics showed that their

strengths and elastic moduli increase by 30–35% as the binder content is decreased from 41 to 10–16 vol %. At the same time, dependences $\sigma(\psi)$ and $E(\psi)$ are of an almost linear ascending character as the binder content is decreased in the range 40–20 vol % typical for workpieces. Moreover, at $\psi = 0.78$ – 0.80 , an acceleration in the increase in strength is observed.

This fact may be explained by the stabilization of the binder interlayer thickness in organic-fiber-reinforced plastics with high reinforcement ratios that is due to extrusion molding of fibers and by an increase in the specific surface of adhesion interactions.

In practice, there are mainly linear dependences of stress–strain properties of composites on the volume contents of fibers. However, at high values of the volume content of fibers, the shear-strength values of organic-fiber-reinforced plastics decrease substantially, while their tensile- and compression-strength values grow.

Cure-Regime Effect

The optimum regime for the cure of organic-fiber-reinforced plastics and load-bearing structures formed on their basis is the temperature–time treatment procedure, which makes it possible to provide the organic-fiber-reinforced plastics with the maximum physicochemical properties and heat resistance, to provide for cure of all of the material layers to avoid possible shape distortions of structures during their exploitation, and to minimize the level of residual stresses caused by heterogeneities in the material structure and by the temperature field in the depths of the walls of workpieces.

One of the most sensitive methods—namely, the method of free torsion vibrations—was used to control the cure process. With the use of this method, the relative stiffness of a yarn impregnated with a polymer binder, a parameter that characterizes the degree of structuring of the binder attained in cure, is determined. An example may be given by the study of the cure kinetics for microplastics based on the Armos yarn with a linear density of 100 tex and the EKhD-MK binder.

The evolution in strength of these microplastics during their cure is shown in Fig. 5. The strength shows a maximum increment as temperature is increased from 353 K (80°C) to 399 K (120°C) for 6 h; then, it decreases to a certain extent. The maximum strength at 393 K (120°C) is explained by the fact that, at this stage, a partially cured binder provides a higher elasticity than does the fully cured binder.

However, this regime (353 K for 4 h followed by 393 K for 2 h) cannot be recommended for the preparation of organic-fiber-reinforced plastics with high tensile and elastic properties, because, in this case, the limiting heat resistance of the composite material is not attained. Moreover, incomplete cure leaves the

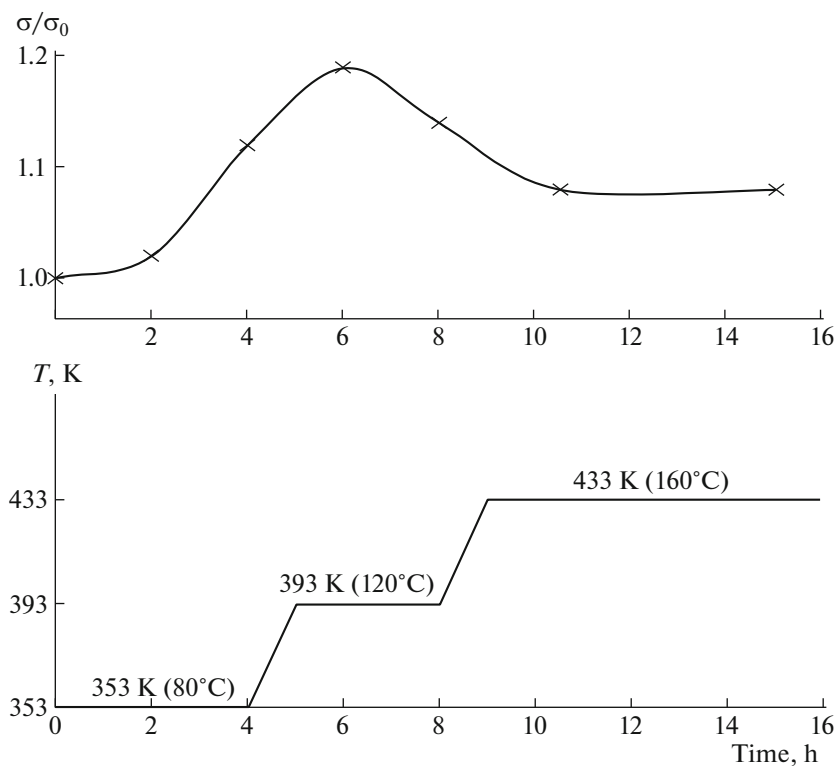


Fig. 5. Change in the tensile strength of the microplastic based on the Armos yarn and the EKhD-MK binder during the cure process.

possibility for shape distortion of structures under operational conditions and may lead to a decrease in stability of a composite against climatic factors. Therefore, in order to achieve the optimum combination of properties of organic-fiber-reinforced plastics based on the indicated fiber, its heat treatment at temperatures of at least 150°C is required.

Effect of Interactions of Fibers with the Binder

An important factor for improvement of the physico-mechanical characteristics of a composite material is the magnitude of adhesion contact between its main components. As was mentioned above, interactions at the interface between polymer fibers based on aromatic polyamides and several epoxy binders may be accompanied by the diffusion of binder components into disordered and defective regions of fibers and may considerably affect binder strength properties in organic-fiber-reinforced plastics.

To study the effect of individual components and the binder as a whole on the morphologies and strength properties of reinforcing fibers, the processes of swelling of SVM and Armos fibers in EDT-10 and EKhD-MK epoxy binders and their components, that is, epoxy oligomers of the ED-20, EKhD, and DEG-1 brands, as well as in *iso*-methyltetrahydrophthalic anhydride (MTHPA), triethanolamine titanate (TEAT-1), and butadiene-acrylonitrile rubber (SKN), were investigated.

The swelling processes were studied by optical microscopy. It was found that, among all of the binder components, EKhD and MTHPA are the most active with respect to fibers.

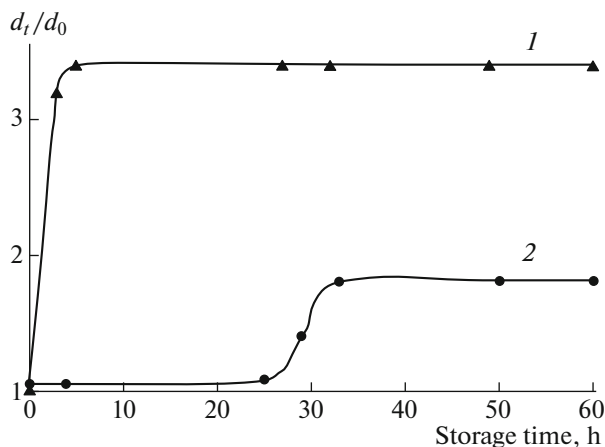


Fig. 6. Curves of swelling of (1) Armos and (2) SVM fibers in the EKhD-MK binder at 293–298 K; d_t is the swollen fiber diameter, and d_0 is the original fiber diameter.

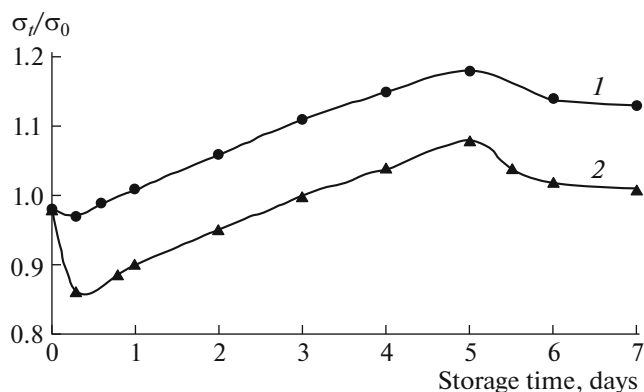


Fig. 7. Changes in the strength properties of (1) SVM and (2) Armos tows during their storage in the EKhD-MK binder; σ_0 is the initial failure stress of the fiber, and σ_t is the failure stress of the fiber kept in the binder for time t .

Figure 6 shows the curves of swelling of the fibers in the EKhD-MK binder. The binder effect is the strongest for the Armos fiber.

Studies (Fig. 7) showed that, for the SVM fiber, an insignificant loss of tensile strength (4%) is observed during the first day of its storage in the binder. At the fifth day, the strength increases to 119%.

The binder effect is more significant for the Armos fiber. Initially, its strength drops by 16% and reaches the initial value only after three days. The maximum value of σ_b for these fibers is 108% with respect to the initial value.

On the basis of the above data, the following mechanism may be assumed for the interaction of binders with fibers. In the initial period of binder contact with the fiber surface, the binder diffuses into the surface region of the fiber, thereby disorienting its fibrils. Then, the outer surface defects are filled; as a result, the fiber structure is ordered, fibrils are bound to each other, and an increase in the transverse strength of the fiber is promoted. A part of the binder penetrates into the interfibrillar space and causes partial disorientation of macromolecules.

The degree of influence of each of these processes is probably determined by both the surface-layer structure of the fiber and the diffusion activity of the binder.

To strengthen the composite material and to enhance the fiber strength in a plastic, it is sometimes advisable to form an intermediate layer on the fiber surface. This layer may prevent disordering of the fiber and create the required (optimum) adhesion fiber-matrix interaction.

It was found that the optimum choice of the finishing composition makes it possible to markedly enhance (up to 15%) the strength properties of organic-fiber-reinforced plastics. In other words, interphase-interaction processes are of great importance.

CONCLUSIONS

With the use of the Armos tow with a thread strength of 5500–5700 MPa in microplastics, samples of unidirectional ring organic-fiber-reinforced plastics with tensile strengths of at least 2550 MPa may be prepared; at least 90% of this strength is preserved at a temperature of 100°C (when the EKhD-MK binder is used). The improvement of the properties of the Armos tow made it possible to increase the thread strength in microplastics to 5.8–6.0 MPa.

The study of properties of organic-fiber-reinforced plastics based on this tow demonstrated that unidirectional organic-fiber-reinforced plastics with a tensile strengths of 3 GPa or above may be produced. In this case, organic-fiber-reinforced plastics based on the EDT-10 binder may be recommended for the production of heavily loaded workpieces operating at room temperature. For workpieces operating at elevated temperatures (100–150°C), the EKhD-MK or EKhD-MD binders should be used to provide the highest level of preservation of strength properties of composite materials during heating.

A promising material for the preparation of high-strength organic fiber-reinforced plastics is the Rusar-S reinforcing filler, which is identical to Armos and

Table 4. Properties of materials based on Armos and Rusar-S aramide fibers

Fiber	Fiber density, kg/m ³	Dry tow breaking load, N	Elastic modulus of yarn, GPa	Number of yarns per tow 600 tex	Twisting of yarn, twists/m	Strength of yarn microplastics, MPa	Variation coefficient for the strength of a threaded microplastic, %	Effective strength of a tow microplastic, MPa	Variation coefficient for the strength of a tow microplastic, %	Threaded microplastics strength in a tow microplastic, %	Average strength of unidirectional organic-fiber-reinforced plastic, MPa	Elastic modulus of unidirectional organic-fiber-reinforced plastic, GPa
Armos	1450	1400	150	6	14	5500	4.0–5.0	4000	4.5–5.5	79.1	2200	85
Rusar-S	1450	1690	165	10	40	6500	2.5–3.0	4450	3.5–4.0	71.1	2800	100

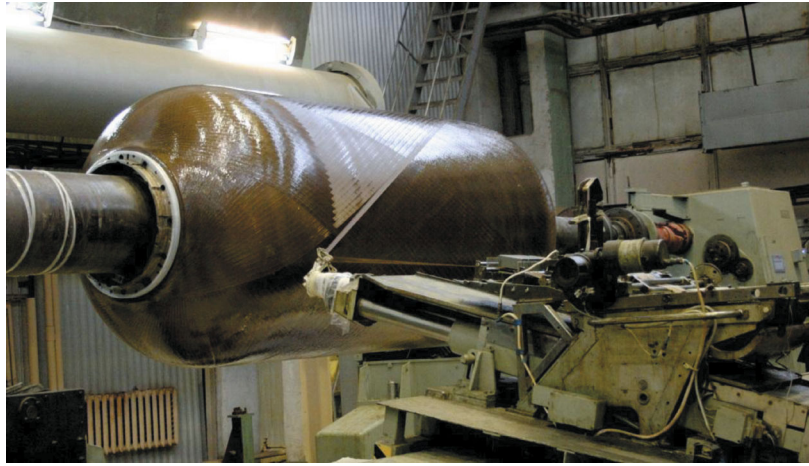


Fig. 8. Preparation of the pressure shell of a bulky workpiece made from an aramide tow by the wet-winding method on a multi-axis winding machine.

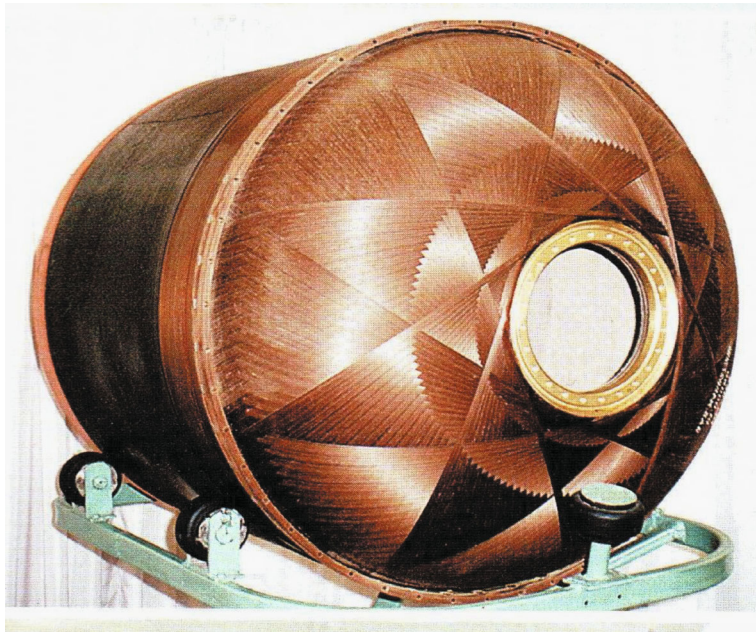


Fig. 9. Rocket-engine case that has a high degree of weight perfection and that is made of the organic-fiber-reinforced plastic.

Ruslan fibers in chemical composition and synthesis parameters. The differences between them are caused by the engineering parameters of the processes of fiber formation from polymer solutions; as a result, the physicochemical and physicomachanical characteristics of the yarns and tows made of these fibers are different: Rusar-S yarns have less breakouts of elementary fibers; are more uniform and “smooth” along their lengths; and are characterized by a higher packing density of monothreads, a lower degree of imperfection of their microstructure, etc. Eventually, this leads to higher physicomachanical parameters of microplastics and unidirectional organic-fiber-rein-

forced plastics based on Rusar-S aramide yarns and tows than those of the analogous materials based on the Armos fiber.

The coefficients of the attainment of yarn strength in a tow microplastic and tow strength in a ring unidirectional composite sample are approximately the same for both materials. Owing to considerably higher parameters of tow microplastics and ring samples, the organic-fiber-reinforced plastic based on the Rusar-S fiber is superior in strength over the organic-fiber-reinforced plastics based on the Armos fiber. This fact was confirmed through testing of workpieces based on the Rusar-S tow. In Table 4, comparative guaranteed



Fig. 10. Lattice structure of the lower coupling section of a Proton-M carrier rocket made of the carbon-fiber-reinforced plastic with the organic-fiber-reinforced-plastic outer shell. The section diameter is 4100 mm, and the height is about 3000 mm.

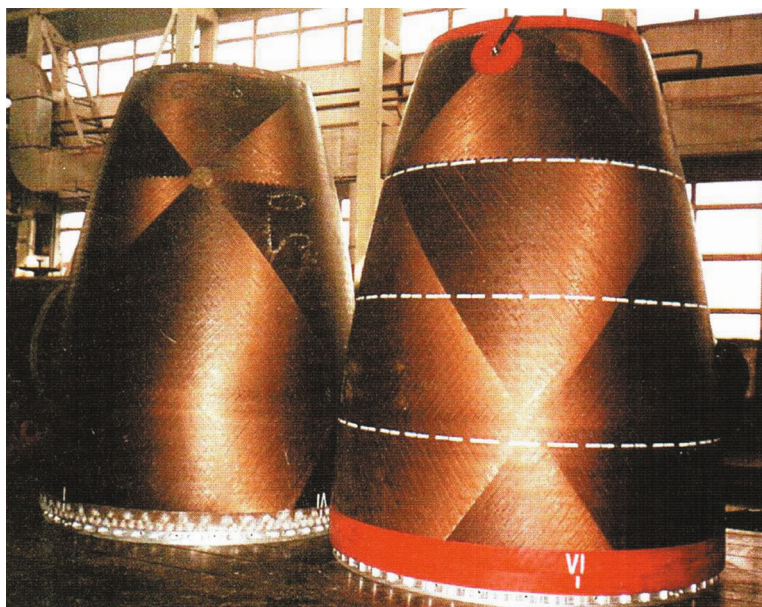


Fig. 11. Samples of workpieces made of polymer composite materials.

characteristics of aramide fibers and organic-fiber-reinforced plastics based on Armos and Rusar-S fibers are presented.

Estimates of the efficiency of application of aramide materials in promising samples of critically important workpieces showed that the use of high-strength organic-fiber-reinforced plastics based on Armos and Rusar-S aramide fibers for the production

of rocket-engine cases makes it possible to enhance the qualitative characteristics of their pressure shells.

The most promising direction of application of aramide and modern carbon materials is the direction related to the creation of light and high-strength composite materials for use in various branches of aviation and engineering.

Figures 8–11 show some bulky workpieces made of polymer composites that were designed, developed, and produced by the method of continuous wet winding of a tow or a yarn on multiaxis winding machines at the OAO Central Research Institute for Special Machinery.

The weight savings for the section made of PCM (Fig. 10) in comparison to an aluminum-stringer prototype is 38%.

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