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АКТУАЛЬНІ ПИТАННЯ СТРУКТУРНИХ ПЕРЕТВОРЕНЬ В ПОЛІМЕРКОМПОЗИТАХ ПІД ВПЛИВОМ ФІЗИЧНИХ ПОЛІВ: ОГЛЯД

В статті проведено аналіз літературних джерел в контексті формування полімеркомпозиційних матеріалів під впливом фізичних полів, які забезпечують інтенсивне структурування композиції на основі реактопластів. Подано характеристику фізичних полів та особливості структурних перетворень на рівні тонкої структури та надмолекулярних утворень, які відбуваються в результаті зовнішнього енергетичного впливу. Доведено позитивний вплив фізичних полів на процеси структурування полімеркомпозитних матеріалів на основі реакційноздатних полімерів за рахунок впорядкування структурних складових, а також формування полімеркомпозитів з низьким напруженим станом та високим ступенем структурування полімерної матриці.

Ключові слова: *механічне поле, тепловий вплив, магнітне поле, електромагнітне випромінювання, ультразвукова обробка, сегменти макромолекул, надмолекулярні утворення, хімічні зв'язки.*

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CURRENT ISSUES OF STRUCTURAL TRANSFORMATIONS IN POLYMER COMPOSITE MATERIALS UNDER THE INFLUENCE OF PHYSICAL FIELDS: A REVIEW

The article analyzes the literature in the aspect of the formation of polymer composites under the influence of physical fields, which provide intensive structuring of the composition based on thermosets. The characteristics of physical fields and the features of structural transformations at the level of fine structure and supramolecular formations, which occur as a result of external energy influence, are presented. The positive influence of physical fields on the processes of structuring of polymer composite materials based on reactive polymers is proven, which is determined by the processes of ordering structural components and the formation of polymer composites with a low stress state and a high degree of structuring of the polymer matrix.

Key words: *mechanical field, thermal field, magnetic field, electromagnetic radiation, ultrasonic treatment, macromolecule segments, supramolecular formations, chemical bonds.*

Problem statement. Improvement of physico-mechanical, thermophysical and operational properties of polymer composite materials occurs due to chemical and physical modification of the polymer network of thermosetting plastics under the influence of energy fields: mechanical and thermal fields, permanent magnetic field, electric field, electromagnetic radiation, infrared or ultraviolet rays, radiation rays or a flow of fast electrons, ultrasonic treatment. The effectiveness of physical modification depends on the chemical structure of the polymer, in particular its polarity, which determines the intensity of the structuring process of polymer composite products, increases the productivity of the technological process, provides the opportunity to automate the processing process and eliminate harmful effects on workers, as well as reduce energy costs and reduce the cost of production.

Analysis of recent research and publications.

The classic technological method for improving the physical and mechanical properties of epoxy composite materials is the use of heat treatment. Heat treatment is usually carried out using automation tools, which allows to increase the productivity of the technological process [1]. With increasing temperature, physical bonds in the epoxy binder are destroyed, which creates conditions for additional structuring. Under the influence of a thermal field, the degree of structuring increases, which is accompanied by an increase in the content of the gel fraction and limitation of the mobility of macromolecules. Therefore, there is a need to increase the temperature of heat treatment to values higher than the glass transition temperature, which increases the mobility of the segments of the epoxy binder macromolecules and leads to a change in the conformational set of the epoxy polymer matrix. At elevated temperatures, the heat treatment process is recommended to be carried out in a stepwise mode [2] to avoid the appearance of residual stresses.

The degree of structuring of epoxy composites depends on the amount of thermal energy, which determines the rate of chemical reaction between the components [3]. At low temperatures, the process of forming a glassy state slows down due to poor diffusion and reduced molecular mobility [4]. During gelation, the rigidity of the skeleton of thermosetting polymer macromolecules increases, which limits the chemical reaction on the side chains. To complete the structuring process, the final temperature of the heat treatment should be 10-15 °C higher than the glass transition temperature. In practice, the temperature of the heat treatment is usually set 50 °C higher than the glass transition temperature, which allows you to reduce the duration of the curing process to two hours or more. However, high curing temperatures directly increase the amount of residual stresses due to the formation of phases with quite different coefficients of thermal expansion (CTE), since a gel fraction is formed in the liquid phase of the binder - a mixture of epoxy resin macromolecules and hardener [5]. Stresses increase as the shrinkage of the structured product increases during cooling from the highest temperature of gel formation to ambient temperature. Polymer composite products based on thermoset polymers are formed under the influence of elevated temperatures, the value of which does not exceed 200 °C, therefore the most common devices for structuring thermosets are resistance furnaces, aerodynamic furnaces and induction furnaces [6]. A significant disadvantage of thermal heating is the appearance of a thermal gradient, which during processing can lead to uneven hardening, an increase in residual stresses and the formation of defects in the formed product.

Structuring in resistance furnaces [7] occurs due to convection processes in the working chamber of the furnace and thermal conductivity of the mold material and polymer composite material, which requires time to equalize the temperature in the volume of the product and the sequence of the structuring process, which begins in the peripheral zone and ends in the central zone of the product. In this case, the product has a higher temperature in the lower part due to the convection distribution of heat flows. Under such conditions, the structure of the polymer composite material is formed in a stressed state, which reduces the mechanical characteristics of the product. The use of aerodynamic furnaces ensures uniform distribution of air flows in the working chamber of the furnace, as a result of which the mold or product is heated simultaneously from all sides, however, the problem of peripheral distribution of thermal energy in the volume of the product is not solved, since energy transfer occurs due to thermal conductivity.

The use of IR radiation [8] in the wavelength range of $76 \cdot 10^{-8}$-10^{-3} m provides uniform heating of polymer composite materials to a greater depth, compared to convection heating in resistance furnaces, where heat transfer occurs in the air flow and due to the thermal conductivity of the polymer material. The penetration depth of IR rays depends on the intensity of absorption by the radiation medium, but the efficiency mainly depends on the spectral properties of the IR source and the optical characteristics of the material. It has been experimentally established that phenol-formaldehyde and epoxy resins absorb IR rays well in the wavelength range of $(2.7\text{-}4.0) \cdot 10^{-6}$ m. This creates an optimal heat flux and ensures the formation of a given material structure with high mechanical characteristics.

Structuring polymer composite products in the field of IR radiation intensifies the synthesis reaction [9] and ensures the formation of a larger number of ordered areas, compared to convective heating. This is due to the direct absorption of energy quanta by polymer molecules, which causes a simultaneous increase in temperature in the thickness of the product and the formation of stronger bonds between the components of the polymer composite material. Under the influence of IR radiation, the processes of heating the material and hardening are combined, which positively affects the productivity of the product molding process, compared to sequential processes that occur using convective thermal energy supply. The formation of polymer composite materials in the field of IR radiation ensures the free removal of moisture and volatile compounds, since there is no densification of the surface layer.

As a result of the treatment of compositions with constant physical fields, the physicochemical properties improve without changing the chemical composition of epoxy composites [10]. This treatment provides regulation of the parameters of the supramolecular structure of the polymer matrix and oriented distribution of filler particles [11] at the interface of the “matrix – filler” phases. An effective method of processing polymer composite materials is the method of forming a composition in a magnetic field [12], which can act as a catalyst or inhibitor of the polymerization reaction and allows changing the topological structure of polymers with the appearance of heterogeneous characteristics of composites. Magnetic processing of polymer composites usually makes it possible to order the structure of the polymer matrix and significantly increase the strength of materials. After magnetic processing in the viscofluid state, a change occurs in the relaxation, mechanical and other properties of polymers. Processing in a constant magnetic field increases the degree of ordering of macromolecules, reduces the size of crystallites and causes anisotropy of supramolecular formations. Epoxy polymers formed under the influence of a constant magnetic flux have anisotropy of optical-mechanical and elastic characteristics with axes of preferential decrease or increase in the values of mechanical and optical properties. The directions of the anisotropy axes change their orientation in the direction of the magnetic flux depending on the isomerism and chemical structure of the hardener.

Polymer composites are classified as weakly magnetic materials due to the presence of a benzene ring and the anisotropy of magnetic susceptibility along and across the macromolecules. Under the influence of external physical fields, the topological structure, which consists of a system of physical and chemical bonds between the molecules of the epoxy binder and finely dispersed particles, changes to an ordered structure with the orientation of the macromolecules in the direction of the field lines [13]. The orientation of fragments of macromolecules with high values of the anisotropy of magnetic susceptibility in a uniform constant magnetic field occurs along the lines of force, and in an inhomogeneous field, the orientation is enhanced due to the additional moment that rotates the macromolecules along the field gradient. The orientation of macromolecules of the polymer binder in a magnetic field provides structural ordering due to the orientation of polymer chains [14], due to which the reactive groups of macromolecules come closer together and additional chemical bonds are formed. It has been established that the orientation of macromolecules in a magnetic field is hindered by the thermal motion of particles, in this case the magnetic field does not affect a separate macromolecule, but a diamagnetic segment. During the synthesis process, the energy of interaction of the magnetic field with the crystal increases. Provided that the energy of the magnetic field and thermal energy are commensurate, the orientation of diamagnetic crystals and structural ordering occur, which positively affects the properties of polymer composite materials. In polymers under the influence of a magnetic field, changes also occur at the level of the supramolecular structure, which leads to a change in the size and shape of the globules of the polymer matrix.

In epoxy compositions, during structuring under the influence of a magnetic field, the size of the globules increases, in addition, the restructuring of the globules into linear structures is possible. The mechanism of structural transformation in polymers is conveniently described using the cluster model, which represents the amorphous structure of the polymer in the form of a set of crystalline clusters with an ordered and compacted arrangement of molecules. Under the influence of a magnetic field, the number of clusters increases, as well as their size and the ordering of macromolecules in them [15]. The heat resistance and mechanical characteristics of polymer composite materials, the structuring of which occurred under the influence of a magnetic field, are higher compared to the physical and mechanical characteristics of polymer composites, the formation of which was carried out under the influence of convective heating. This is explained by the formation of stronger physical and chemical bonds between macromolecules in the middle of the cluster, as well as an increase in their number [16]. In work [17], based on the results of the analysis of X-ray structural studies of an epoxy polymer structured in a constant magnetic field, a compaction of the spatial structure of molecules was recorded as a result of the appearance of an orientation effect under the influence of a magnetic field. The epoxy polymer, which is structured under the influence of external physical fields, becomes capable of anomalous thermal expansion and an increase in the density of the composite. At the same time, polymer composites based on epoxy resin containing metal oxide particles, which are structured under the influence of external physical fields, are characterized by lower values of the thermal coefficient of linear expansion, which is explained by the higher density of the polymer network.

In the process of forming the structure of the epoxy polymer under the influence of a magnetic field, a new complex of thermodynamic, thermophysical, thermomechanical properties is formed, and the mechanical characteristics of epoxy composite products also increase [18]. In polymethyl methacrylates, under the influence of an external magnetic field, a crystalline and supramolecular structure that is more resistant to external loads is formed, which is not distinguished by high thermal stability.

In the process of creating composites based on amorphous polyurethane under the influence of a permanent magnetic field, the formation of long-range order in the polymer matrix does not occur, and a decrease in heterogeneity is recorded as a result of the destruction of the system of intermolecular hydrogen bonds [19]. A permanent magnetic field increases the homogeneity of the initial polymers and mixtures, which improves the thermal and thermomechanical properties of the composites. This allows you to expand the scope of application of polymer composites by giving the materials new properties (conductivity, dielectric permittivity). Polymer composites with dispersed ferromagnetic fillers, which are structured under the action of an external permanent magnetic field, have a better ability to orient fragments of macromolecules than composites with a diamagnetic type of filler. In the process of structuring epoxy composite materials under the influence of external fields, the orientation of fragments of macromolecule chains around particles of finely dispersed filler occurs, which increases their mechanical characteristics [20]. On the surface of ferromagnetic particles under the action of an external magnetic field, a surface layer with a high degree of structuring is formed, which provides an increase in the adhesive and cohesive strength of the epoxy composite material. This is due to the existence of a double electric layer at the phase interface. Most polymers are dielectrics that have the ability to polarize under the influence of an external constant electric field. In the case of a dielectric in an electric field, the centers of gravity of negative and positive charges are displaced relative to their equilibrium positions, resulting in electric polarization of the medium [21]. The following types of dielectric polarization are characteristic of polymers: electronic polarization, which occurs as a result of the displacement of the orbitals of electron motion under the influence of an external field; atomic polarization, which is due to the displacement of atomic nuclei; dipole polarization, which is associated with the thermal motion of macromolecule fragments. The polarization of polymer dielectrics is determined by the number of dipoles per unit volume of the polymer, and also depends on the interaction between macromolecules and the dipole moment of the macromolecule link [22].

Under the influence of an electric field, the neutrality of macromolecules is disturbed and polarization of macromolecule fragments occurs, which is accompanied by the opposition of macromolecules to the formation of an energetically favorable conformation [23]. The packing density of polymer macromolecules after treatment in an electric field increases, which is determined by a higher density and a higher softening temperature. Polymer polarization occurs as a result of the arrangement of macromolecule chain fragments in such a way that their dipole moments and polarized bonds are oriented in the direction of the lines of external field strength.

Uniform distribution of thermal energy in the volume of polymer composite products occurs as a result of the absorption of electromagnetic radiation energy generated by ultrahigh frequency sources [24]. This method provides increased productivity, improves product characteristics, promotes uniformity of the structuring process, reduces the required production space and process control, intensifies the heating process of the polymer composite product, allows you to control the temperature, and also stops the heating process after turning off the source of electromagnetic waves [25]. Processing of epoxy compositions without a hardener using high-frequency electromagnetic pulse irradiation allows you to predictably control the processes of structure formation and increase the performance characteristics of epoxy composites.

Electromagnetic heating of conductive metals occurs as a result of the action of a magnetic field, and heating of dielectric polymers occurs under the influence of an electric field. During processing in a high-frequency electromagnetic field, better temperature control is provided compared to thermal curing [26]. Polymers with low moisture content and at low temperatures exhibit dielectric properties, however, in the case of increasing moisture content or heating, the polymers become semiconductors. This determines the dominant influence of the electric or magnetic component of the electromagnetic field. Heating of polymers occurs as a result of direct absorption of energy by the material due to the movement of ions and oscillations of dipoles with the frequency of oscillations of the electromagnetic field without changes in the structure of molecules. During the influence of a high-frequency electromagnetic field, a simultaneous and uniform increase in temperature occurs throughout the volume of a homogeneous material due to the dissipation of the electric field energy, since dielectric energy losses occur, which are associated with overcoming the interaction of polarized molecules [27] of polymers.

Processing of polymers in an ultrahigh-frequency electromagnetic field provides intensive heat generation in the material, and the heating is uniform throughout the volume of the material. In addition, since the energy is supplied directly to the material, the heat energy consumption for heating the equipment is reduced, as well as heat losses for convection and radiation from the mold surfaces. In an electromagnetic field, with increasing field frequency, the dielectric constant decreases, which indicates an increase in the degree of structuring and the formation of a denser spatial network [28]. Under the influence of high-frequency treatment, polymerization occurs by a step mechanism, polymerization with ring opening, and also radical polymerization [29]. As a result of the influence of a high-frequency electromagnetic field, the physicomechanical and tribological properties of polymer composites improve due to the ordering of the supramolecular structure of the polymer matrix [30].

The authors of [31] conducted a study of the influence of an ultrahigh-frequency electromagnetic field on the strength and thermomechanical characteristics of epoxy composites. Graphite-filled epoxy composites after treatment in an electromagnetic field have a strength that corresponds to the strength values of epoxy composites structured by the thermal method. A significant advantage of structuring in a field of ultrahigh-frequency currents is the reduction of the process duration.

In [32], a positive effect of ultrahigh-frequency treatment on the adhesion and strength characteristics of epoxy composites was determined. At the optimal time of electromagnetic treatment of the plasticized epoxy matrix, the adhesion strength increases by 35%, compared with untreated epoxy polymer samples. The increase in this characteristic occurs due to the formation of radicals and an increase in the number of paramagnetic centers in the binder under the influence of electromagnetic treatment. In the process of structuring, radicals and paramagnetic centers recombine, which leads to the formation of additional physical bonds with the surface of the metal substrate.

The high intensity of the structuring process is determined by the rate of formation of active centers [33] under the influence of radiation. This processing method is convenient in the technological process, since it allows you to control with high accuracy the initialization of the structuring process, the speed and temperature of the reaction as a result of changing the intensity of the energy flow. A significant disadvantage of the method is the high sensitivity of the polymer matrix to the intensity of radiation radiation. The use of fillers leads to the absorption of part of the energy, which as a result will not be enough for polymerization, however, in the case of an increase in the radiation dose, the mechanical properties of the polymer composite material deteriorate and the destruction of the polymer matrix is possible. The use of a stream of accelerated electrons as radiation radiation allows the use of large doses of radiation, since the stream of electrons interacts directly with atoms and electrons of the substance, as a result of which their kinetic energy is lost. This has a positive effect on increasing the productivity of the processing of polymer composite products, however, the depth of the layer in which the structuring processes occur under the influence of the flow of accelerated electrons does not exceed 2 mm. In this case, it is necessary to form products using layer-by-layer application of a polymer binder, which limits the unification of the application of processing for different technologies for forming polymer composite products. In the case of electron irradiation of polyethylene at lower absorption doses, the degree of crystallinity decreases, and at higher absorption doses, this degree increases. Electron irradiation at low absorption doses leads to simultaneous processes of destruction of the main chain and side branches, as well as to crosslinking of polyethylene macromolecules [34].

The effect of elastic vibrations of the sonic and ultrasonic frequency ranges on liquids allows for the widespread use of such vibrations to intensify technological processes (dispersion, emulsification and preparation of suspensions, mixing of various components, polymerization) during the production of polymer composite materials [35]. Ultrasonic vibrations provide a high level of dispersion, while increasing the interfacial surface of the reacting components. The use of mechanical vibrations of the ultrasonic range or low-frequency ultrasonic vibrations (vibration treatment) is one of the dominant methods in the production of classical polymer composites and nanocomposites and the most promising means of physical modification of liquid epoxy resin or solid components used in chemical technology to intensify technological processes for structuring epoxy composite products [36].

High-frequency sound treatment of the composition before hardening provides a more ordered and less defective structure, which contributes to increasing the strength of polymers [37]. Ultrasonic treatment improves the conditions for homogenization of the mixture, sharply reduces the viscosity of the composition and improves the hardening kinetics of epoxy composites. Treatment of the composition with ultrasonic vibrations ensures the formation of a less stressed structure of epoxy composites, which indicates a minimal exothermic effect and a more homogeneous nature of structuring, since the relaxation processes occur at maximum speed [38]. As a result, ultrasonic treatment allows you to increase the adhesive strength, deformation-strength and operational characteristics of polymer composite materials, as well as reduce the level of residual stresses [39]. This type of treatment contributes to the manufacture of defect-free and monolithic structures from reinforced polymer composites, which is determined by the ability of low-frequency ultrasound to destroy agglomerates of nanodispersed particles and ensure uniform distribution of the filler in the volume of the polymer matrix.

The author of the work [40] determined that one of the promising directions for creating protective polymer composite coatings with high physical and mechanical characteristics is the treatment of the composition with external physical fields. Ultrasonic treatment allows to increase the adhesive strength by 25-30%, the impact strength by 50% and to reduce the heat treatment temperature by 20-30%. The optimal treatment mode in an alternating electromagnetic field at a frequency of 40 MHz for 2-3 min was determined, as a result of which the adhesive strength increases by 4-8 MPa. Treatment of the composition in a field of ultrahigh frequency currents improves the process of structure formation and allows to reduce the residual stresses of the coatings by 20-25%, which occurs due to the formation of a dense and homogeneous spatial epoxy polymer network and the passage of relaxation processes. Complex treatment in external physical fields allows to additionally increase the adhesive strength by 15-20% and reduce residual stresses by 30%.

In [41], the need for complex ultrasonic and high-frequency electromagnetic treatment of epoxy binder containing ferromagnetic nanodispersed filler was identified. The influence of physical fields ensures spatial orientation of the filler and a high degree of structuring of the composite due to the formation of a uniformly distributed spatial network of epoxy polymer.

Treatment of epoxy compositions in a viscous-fluid state with ultraviolet rays in low doses for short periods of time leads to cracking of macromolecule chains [42], which will occur for the following reasons:

– due to ultraviolet irradiation of the epoxy composition, the potential energy of the heterogeneous system increases, which is accompanied by a change in interatomic distances and valence angles in the macromolecular chains. The increase in the internal energy of the system causes the localization of potential energy in individual sections of the macromolecular chains. This leads to the formation of an active state in such sections, which is characterized by increased stress and destruction of chemical bonds. In this case, there is a redistribution of potential energy between the oligomer macromolecules;

– ultraviolet treatment of epoxy compositions is carried out in an air environment, in which oxygen molecules are acceptors and are able to interact with the atoms of the main chain. The interaction of oxygen molecules with oligomer macroradicals leads to the formation of stable peroxides, which cause the destruction of the epoxy resin macromolecule chains;

– the introduction of dispersed mineral additives also accelerates the destruction of macromolecules as a result of a change in the conformation of macromolecules and the initiation of free radicals. Important in this case is the magnetic and chemical nature of the dispersed filler, as well as the topology of its surface. Active centers that are formed on the surface of dispersed particles under the action of ultraviolet radiation are not necessarily localized near it, since this is not always energetically advantageous. This leads to a change in the position and movement of the polymer macromolecule node, which causes the isomerization of the macroradical.

As a result of experimental studies, a positive effect of the influence of acceptors of different nature on the formation of radicals and the structure formation of composites during ultraviolet treatment was determined [43]. The formation of free radicals occurs as a result of the complex effect on macromolecules of oligomers of ultraviolet radiation and thermal treatment of filler particles, which leads to an increase in the chemical and thermodynamic activity of the dispersed filler. During ultraviolet treatment, the increase in the number of free radicals provides an increase in the degree of structuring of the binder in the outer surface layers, which significantly improves the physical and mechanical properties of epoxy composite materials.

Treatment of epoxy compositions with ultraviolet rays provides an increase in the rate of structuring of the matrix and a significant increase in the degree of gelation of the material [44]. The results obtained are determined by the formation of active free radicals, which intensively interact with the surface of the filler and macromolecules of the matrix. Ultraviolet treatment of the matrix intensifies the process of structure formation, which leads to an increase in the stiffness of the composite.

In [45], as a result of preliminary irradiation of epoxy resin with ultraviolet light, there is a decrease in the adhesion strength of coatings regardless of the physical nature of the finely dispersed filler. At the same time, ultraviolet irradiation of epoxy compositions leads to an increase in the cohesive strength of coatings, which is due to the formation of outer surface layers of a certain thickness around finely dispersed particles.

As a result of complex treatment (ultraviolet irradiation and magnetic treatment) of the composition [46], the cyclic strength of epoxy composite coatings increases. Treatment with ultraviolet irradiation of epoxy resin followed by magnetic treatment of the composition provides an increase in the endurance limit of the “substrate - coating” system by 1.8-2.0 times, compared to the untreated system.

One of the main tasks in the process of forming epoxy composites is to ensure optimal conditions for physicochemical interaction at the “binder-filler” phase interface. An important stage in solving such a problem is to obtain information about the interfacial interaction of binder macromolecules with active centers on the surface of mineral filler particles during the process of forming the material, as well as determining the influence of this interaction on the properties of epoxy composites during operation.

Conclusions. Physical modification of polymer composite materials consists in processing compositions at the structuring stage with energy fields, which increases the intensity and productivity of the process of forming polymer composite products, and also provides the opportunity to automate and shorten the processing process, which allows eliminating harmful effects on workers and reducing energy costs.

As a result of processing an epoxy composition in a thermal field, physical bonds are destroyed, which leads to a decrease in viscosity and an increase in the mobility of segments of macromolecules of the epoxy binder with a subsequent change in the conformational set. Thermal treatment of epoxy composites is regulated by an optimal temperature-time regime, which provides a high degree of structuring of the system with low residual stresses. A significant disadvantage of thermal structuring is the uneven distribution of thermal energy in the volume of the polymer composite product, which leads to an increase in the level of the stressed state and a decrease in mechanical characteristics.

A more effective method of structuring is the irradiation of the composition with infrared rays, which are able to penetrate to a greater depth and initiate the process of forming a network structure with stronger chemical bonds.

Under the influence of magnetic treatment, the parameters of the supramolecular structure of the polymer matrix are adjusted and the filler particles are oriented at the interface of the “matrix-filler” phases, which allows the structure to be ordered due to the orientation of macromolecules in the direction of the magnetic flux. This ensures the approximation of the reactive groups of the epoxy binder with the formation of additional chemical bonds.

Epoxy resin macromolecules are polarized in an electric field, which is determined by the displacement of the centers of electric charges, as a result of which the packing density of the polymer network increases, conformational transformations occur and the interaction between macromolecules improves.

Processing of compositions in a microwave field provides uniform absorption of electromagnetic radiation energy, which is accompanied by heat generation as a result of overcoming the interaction of polarized polymer macromolecules. Such processing provides the formation of a denser spatial network, increases the uniformity of the structure and intensifies the process of structuring epoxy composites.

The use of radiation irradiation methods allows structuring without hardeners, however, polymer systems are quite sensitive to the intensity of such an energy field, which complicates the process of forming epoxy composite products.

Ultrasonic treatment is advisable for compositions containing highly dispersed fillers, which provides a high degree of dispersion of components and uniformity of the structure of polymer composites with a lower content of defects.

Under the influence of ultraviolet radiation, the number of free radicals increases, which significantly increase the degree of gelation of the material and the degree of structuring of the binder in the outer surface layers.

The scientific approach and practical implementation of the processes of structuring epoxy composite products consists in determining the optimal treatment mode of the composition of a given composition in energy fields, which will allow obtaining the predicted structure of the polymer matrix and forming an epoxy composite material with high performance characteristics.

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