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A.Yu. Poloz^a, *N.R. Prokopchuk*^b, *R.M. Dolinskaya*^b, *Yu.R. Ebich*^c**THE INFLUENCE OF POLYAMINES ON THE PROPERTIES OF EPOXY COMPOSITES**^a LTD «New Technologies», Dnipro, Ukraine^b Belarusian State Technological University, Minsk, Belarus^c Ukrainian State University of Chemical Technology, Dnipro, Ukraine

The viscoelastic properties of epoxy resin-based composites ED-20 in a mixture with aliphatic epoxy resin DEG-1 have been determined as functions of the applied industrial polyamine hardener and additional heat treatment (at the temperatures of 60–140°C). The differences in the thermomechanical and physical-mechanical properties, and wear resistance of the composites have been stated resulted from the change in the ratio of the energies of elastic and viscous deformation. The ratio of the energies of elastic and viscous deformation of composites in a dynamic loading mode is influenced by the formed spatial cross-linked structure of the epoxy matrix. The effects of the temperature of additional heat treatment on the change in thermomechanical properties and the nature of the destruction of epoxy composites have been shown. It has been proposed to apply a combined heat treatment conditions (80+100°C). To achieve optimum viscoelastic properties after hardening at 20°C, it is expedient to heat-treat the obtained epoxy composites in a vitreous state at temperatures close to vitrification temperature and use a Polyamine B hardener.

Keywords: epoxy resin, polyamine hardener, cross-linked structure, viscoelastic properties, wear resistance.

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Introduction

Epoxy composites possess a number of important operational properties such as high durability, adhesion to various types of substrata, wear resistance, resistance to various media [1,2]. They are widely used in the production and repair of parts that are operated under the conditions of the intensive impact of abrasive media [3–5]. For such composites, epoxy resins are most commonly used with aliphatic epoxy-containing diluents, which are applied to reduce their viscosity and participate in the formation of mixed network structures. The curing of these compositions is carried out with polyamines using energy-saving technology at the temperature of 20°C, followed by further curing at 80–120°C [6]. The kinetic features of the curing of mixtures of dianic and aliphatic epoxy resins with aliphatic polyamines have been discussed elsewhere [7]. At the same time, the conditions of time-temperature curing, the chemical nature and concentration of polyamine hardeners that affect the exothermic reaction of the interaction of epoxy resin

groups with amine hardening groups, wear resistance under conditions of contact dynamic loading [8], viscoelastic and other operational properties of composites were to a considerable degree overlooked. However, these data are necessary to correctly select appropriate polyamine hardeners in fabricating the required technological and operational properties, taking into account the expansion of the market of the used hardeners.

Therefore, the objective of this study was to determine the most important operational properties of epoxy composites under static and dynamic conditions in order to promote understanding of the mechanism for ensuring the working capacity of composite materials under critical conditions. The main attention was paid to the role of the ratio of elastic and viscous characteristics of epoxy composites in ensuring their operational properties.

Experimental

Epoxy-diane resin ED-20 was used as an epoxy matrix ($M_n=390$ g/mol, the content of epoxy groups was 21.8 wt.%), whereas diglycidyl ether of diethylene

glycol DEG-1 (the content of epoxy groups was 25.7 wt.%, dynamic viscosity was equal to 0.07 Pa·s at 25°C) was used as an active thinner (10 wt.–100 wt., resin). The low-viscosity light liquids that were used as polyamine hardeners met the standards of producing companies. The hardeners were added in the quantities recommended by manufacturers and had the following characteristics: polyethylene polyamine is a mixture of linear and branched ethylene and piperazine containing ethylene polyamines from diethylenetriamin and N-aminoethylpiperazine to compounds with 6–7 nitrogen atoms, dynamic viscosity (η) equals 90 mPa·s at 25°C, amine number (A) is equal to 205 mg KOH/g; Polyamine B is a mixture of a tetraethylenepentamin, pentaethylenegexamine, hexaethylenheptamine and amines with higher molecular weight, the content of a tetraethylenepentamine (TERA) is 15 wt.%, the content of amines with higher boiling point than the boiling point of pentamines is 83 wt.%, the content of amines with lower boiling point is equal to 1 wt.%; Ancamine 2692 is the modified cycloaliphatic polyamine, $\eta=120$ mPa·s, A=300 mg KOH/g; Ancamine 2686 is the modified cycloaliphatic polyamine, $\eta=135$ mPa·s, A=310 mg KOH/g; Ancamine 2752 is the modified cycloaliphatic polyamine, $\eta=390$ mPa·s, hydrogen equivalent (H) of 95 g/eq; Ancamine 1638 is the modified aliphatic polyamine, $\eta=100$ mPa·s, A=1070 mg KOH/g, H=31 g/eq; CeTePox 1410 H is the modified cycloaliphatic polyamine, $\eta=550$ mPa·s, H=95 g/eq; and Epikure F-205 is the modified cycloaliphatic polyamine, $\eta=500$ mPa·s, H=105 g/eq.

Compositions were prepared by introducing epoxy-diane resin ED-20 and active thinner into the reactor of periodic action at the temperature of 60°C, the components were mixed for 15 minutes. Polyamine hardeners were previously added to compositions at the temperature of 20–25°C and mixed for 5–7 minutes. The prepared compositions were poured into the relevant molds and cooled with the use of energy-saving procedure at 20±2°C during 24 hours. The samples were subjected to the heat treatment at 60–140°C for 3 hours, and they were also heat-treated under the optimized conditions at 80+100°C in order to improve the properties of composites.

The exothermic reaction of hardening was studied with the constant amount of resin (50 g) in compositions using thermocomplex supplied with the thermocouple and the display with temperature readings in the center of composition volume [9].

The temperature readings were taken every 2 minutes, fixing the maximum temperature of the

reaction and its reduction. When processing the data of temperature change of the exothermic reaction of hardening, the onset of gelation was found by extrapolation a tangent to the experimental curve of rise in temperature of composition in the main period to the axis of abscissas.

The rate of temperature change in the main period of the hardening reaction (at a sharp rise in temperature, °C/min) was determined from the tangent of the angle of inclination of the tangential temperature change from the gel point to the point with the maximum temperature taking into account the duration of this period [9].

The course of hardening reaction and formation of the cross-linked structure of composites were characterized by the contents of sol-fraction (S), cross-linked coefficient (γ), the average molecular mass of interstitial chains (M_c), and the cells size formed by interstitial chains of polymers according to the X-ray diffraction analysis.

The content of sol fraction in the samples was determined from the change in their mass after extraction with acetone during boiling in a Sokslet's device for 6 hours. The cross-linked coefficient, γ , was calculated with the use of the following formula [10]:

$$\gamma = \frac{1/S^{0.5} - 1}{1 - S}.$$

The average molecular mass of interstitial chains (M_c , g/mol) and the equilibrium modulus of high-elasticity (E_e , MPa) were calculated on the basis of the thermomechanical measurements according to the following equations [11,12]:

$$M_c = \frac{3\rho RT_e}{E_e}; \quad E_e = \frac{F}{S} \cdot \frac{h}{\Delta h},$$

where F is the permanent load of a sample, H; S is the cross-sectional area of a sample; h_0 is the initial height of a sample, mm; Δh is the deformation of a sample upon reaching a highly elastic state, mm; ρ is the polymer density, g/cm³; R is the universal gas constant ($R=83,14$ kgf·cm/mol·K); T_e is the temperature of transition to a highly elastic state, K; and E_e is the equilibrium module of high-elasticity, MPa.

The temperatures of glass transition, T_g , and transition to the highly elastic state, T_e , of the cured samples were also determined by the thermomechanical method. The measurements were performed using cylindrical samples (10 mm in diameter and height) with permanent unit load equal to 0.75 MPa,

the heating rate was 4°C/min.

The X-ray diffraction analysis of the composites was conducted by using methods of wide-angle and small-angle scattering of X-rays. Wide-angle X-ray scattering was carried out using the X-ray diffractometer with the slit-type collimation of X-rays primary beam and the X-ray optical scheme based on primary beam «passing» through the sample.

Small-angle X-ray scattering was carried out using the small-angle X-ray camera equipped with the Kratky-type slit collimator. The geometric parameters of the camera satisfied the condition of infinite height of the primary beam [13].

X-ray diffraction study was performed at the temperature of 22°C in CuK_α radiation (wavelength $\lambda=0.154$ nm), monochromated with a Ni filter.

Because of extension of the epoxy composites' scope of application, their properties were defined under the static and dynamic conditions. The main physical-mechanical properties were determined under the static conditions on flat samples 15 mm width, 10 mm thick and 125 mm length according to the accepted standards. The samples were viscoelastic at the temperature of $22\pm 2^\circ\text{C}$ under the dynamic conditions; IPM-1K device was used [14] according to the relevant mathematical dependences. The device uses a dynamic indentation method, which consists in striking by means of a rigid indenter on the tested composite in a single pulse mode [14]. Under impulsive loading, the composite shows viscoelastic properties that cannot be estimated in case of static influence; in addition, dynamic loading simulates the most stringent conditions that a composite material can undergo during operation. Viscoelastic properties were characterized with the use of the models of Maxwell and Kelvin-Voigt. The Maxwell model describes the stress relaxation of a solid to a first approximation, and the Kelvin-Voigt model describes its creep [15].

The wear resistance of the composites was estimated under the conditions of rigid gas-abrasive wear of samples (20×15×4 mm) by a sand particle flow of 0.5–0.9 mm at a speed of 76 m/s on a centrifugal solid particle accelerator at different abrasive attack angles: 15°, 30°, 45°, 60° and 90°.

Results and discussion

Polyamines are widely used as hardeners for cold-cured epoxy composites, in particular polyethylene polyamine (PEPA), in amounts close to stoichiometric ones (9–12 wt. per 100 wt. ED-20). The concentration of the hardener determines the spatial cross-linked structure of the composites and, therefore, their viscoelastic properties, wear resistance and other characteristics.

According to Fig. 1, the unfilled epoxy composites obtained using 10–12 wt. of PEPA possess optimum viscoelastic properties and shows the minimum values of mechanical loss angle tangent.

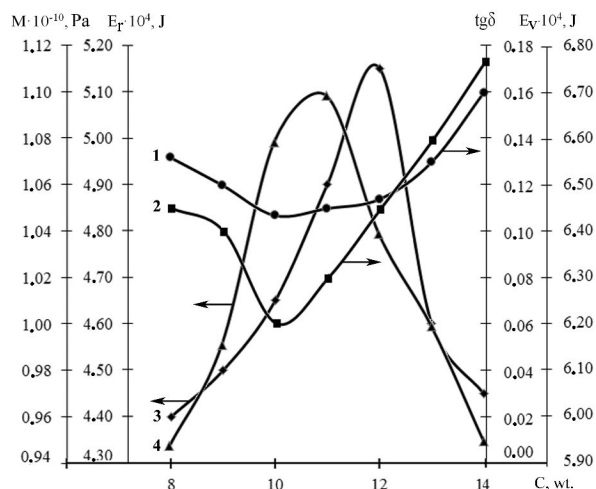


Fig. 1. The effect of polyethylene polyamine concentration (C) on the properties of ED-20 epoxy-based composites: 1 – mechanical loss angle tangent, $\text{tg}\delta$; 2 – energy of viscous deformation E_v ; 3 – modulus of elasticity M ; and 4 – energy of resilient deformation E_r .

Excess hardener (14 wt.) is a plasticizer which decreases the dynamic module of elasticity, deformation energy and increases the energy of viscous deformation.

Wear resistance of composites corresponds to the values of the deformation energy and its component, the energy of elastic deformation.

Polyamine hardeners of various manufacturers have different impacts on the course of the exothermic reaction of hardening during the interaction of epoxy resin groups with amine groups of polyamines.

The developed temperature during this reaction influences a number of important technological parameters (the «viability» time associated with the course of jellification process, the rate of temperature increase during hardening, etc.) and the operational properties related to the uneven distribution of the created three-dimensional grid with the rapid increase in the high temperature of reaction.

As shown in Table 1, the maximum temperature of an exothermic reaction and maximum temperature change rate in the main period are observed for Ancamine hardeners; the lowest temperature of exothermic reaction of hardening is achieved when

Table 1

The effect of industrial polyamines on the process of epoxy compositions hardening and their properties (hardening conditions: 20°C×24 h+100°C×3 h)

Indicators	Polyamines							
	CeTe-Pox 1410 H	Epikure F-205	Ancamine 1638	Ancamine 2692	Ancamine 2686	Ancamine 2752	Polyamine B	PEPA
Concentration of a hardener, wt.	54	58	15	50	50	50	10	10
Parameters of exothermic reaction of hardening:								
maximum temperature, °C	118	120	156	134	138	133	98	124
time of the beginning of jellification, min	22	22	16	34	32	34	29	32
rate of change of temperature in the main period, °C/min	9.13	4.00	28.50	10.20	11.70	10.13	4.37	3.67
Parameters of three-dimensional structure:								
maintenance of zol-fractions S, wt. %	0.18	0.17	0.33	0.33	0.31	0.38	0.24	0.28
cross-linked coefficient γ	22.9	23.5	16.4	16.4	16.9	15.2	19.4	17.9
Physical-mechanical properties:								
impact strength determined according to the Charpy method, kJ/m ²	15.0	16.5	10.0	9.7	10.5	9.2	14.8	14.3
flexural strength, MPa	87	84	95	98	96	110	91	92
tensile strength, MPa	30.0	30.8	35.4	36.1	36.7	37.6	28.1	22.3
relative deformation at stretching, %	13.0	12.7	15.0	15.0	15.5	16.0	13.5	13.6
compressive strength, MPa	146	138	155	155	157	150	160	156
Viscoelastic properties at dynamic loading:								
modulus of elasticity $M \cdot 10^{-10}$, Pa	1.36	1.43	1.30	1.29	1.31	1.27	1.33	1.32
mechanical loss angle tangent, tg δ	0.097	0.093	0.114	0.111	0.113	0.110	0.108	0.109
energy of deformation $E_d \cdot 10^3$, J	1.097	1.114	1.060	1.059	1.064	1.031	1.085	1.072
energy of elastic deformation, $E_e \cdot 10^4$, J	5.811	6.656	5.210	5.201	5.266	4.916	5.563	5.375
energy of viscous deformation, $E_v \cdot 10^4$, J	5.159	4.484	5.390	5.389	5.374	5.394	5.287	5.345
viscosity determined according to the Kelvin–Voigt model, N·s	6.53	6.63	6.30	6.27	6.37	6.09	6.46	6.42
viscosity determined according to the Maxwell model, N·s	665	765	465	444	524	444	549	530
Deterioration ($\Delta V \cdot 10^3$, cm ³) at abrasive angles of attack equal to:								
15°	5.4	2.4	9.0	9.4	7.5	13.7	6.6	7.0
30°	12.7	10.7	20.9	22.8	16.1	28.5	14.7	15.4
45°	14.7	15.9	22.2	24.1	18.4	30.5	17.2	17.8
60°	8.5	6.6	13.4	14.0	12.5	17.6	10.8	11.9
90°	2.4	1.0	8.0	8.3	7.0	12.5	5.7	6.1

using a hardener of Polyamine B.

High temperature of the exothermic hardening reaction and the rate of its change in the main period as well as the heat release rate during this process result in an uneven course of the process of three-dimensional grid formation and an increase in the proportion of resin macromolecules in the grid.

Indeed, the deepest course of the hardening process according to the sol-gel analysis (Table 1) and the maximum degree of cross-linking of the epoxy composites are observed when using Epikure F-205, CeTePox 1410 H and Polyamine B hardeners, which provide more favorable hardening conditions at a lower temperature rise rate in the main period. Rather high rate of change in the temperature of the

exothermic hardening reaction in the presence of Ancamine hardeners leads to a smaller degree of completeness of the process, which is reflected in wear resistance under the conditions of intensive gas-abrasive wear of composites, their physical-mechanical and viscoelastic properties.

It is known [7] that the use of dynamic methods of mesh polymers research allows characterizing the degree of functional groups transformation and the density of cross-links in mesh polymer by the modulus of elasticity. Table 1 shows that there is a strong correlation between the dynamic modulus of elasticity and cross-linking coefficient of epoxy composites.

Other viscoelastic properties of epoxy

Table 2

The effect of the additional heat treatment temperature on the properties of unfilled epoxy composites (the duration of heat treatment is 3 hours after the main hardening according to the 20°C×24 h mode; the PEPA hardener)

Indicators	Heat treatment temperature, °C						
	without heat treatment	60	80	100	120	140	80+100
Parameters of three-dimensional structure:							
maintenance of zol-fraction S, wt.%	13.96	3.58	3.07	2.18	2.45	3.74	0.32
cross-linked coefficient γ	1.95	4.44	4.86	5.90	5.53	4.33	16.73
average molecular mass of interstitial chains of M_c , g/mol	6519	4795	2612	1370	1586	2733	932
Glass transition temperature T_g , °C	70	73	95	115	114	93	118
Temperature of transition to a highly elastic state T_e , °C	77	84	108	129	127	105	132
High-elasticity modulus E_e , MPa	1.76	2.45	4.89	9.91	8.49	4.62	14.68
Viscoelastic properties at dynamic loading:							
modulus of elasticity $M \cdot 10^{-10}$, Pa	0.86	0.90	0.97	1.01	1.03	0.89	1.02
mechanical loss angle tangent, $\text{tg}\delta$	0.143	0.128	0.116	0.107	0.114	0.137	0.108
energy of deformation $E_d \cdot 10^3$, J	1.082	1.096	1.111	1.134	1.122	1.103	1.138
energy of elastic deformation, $E_e \cdot 10^4$, J	4.205	4.258	4.658	4.827	4.952	4.471	4.998
energy of viscous deformation, $E_v \cdot 10^4$, J	6.615	6.702	6.452	6.513	6.268	6.559	6.382
viscosity determined according to the Kelvin–Voigt model, N·s	6.00	6.37	7.05	7.42	7.65	6.59	7.85
viscosity determined according to the Maxwell model, N·s	478.5	510.1	525.6	530.5	614.1	518.2	658.9
The maximum wear at gas-abrasive influence, $\Delta V \cdot 10^3$, cm^3	22.0	21.1	16.8	15.0	11.2	18.2	5.0

composites are also caused by the formed three-dimensional structure: when cross-linking is reduced, the energy of elastic deformation decreases whereas the energy of viscous deformation increases. The high values of the elastic deformation energy achieved with Epikure F-205 and CeTePox 1410 H hardeners ensure increased wear resistance of epoxy composites under the conditions of intense gas-abrasive wear. With an increase in the proportion of inelastic deformations, the use of Ancamine hardeners increases deformation and strength at the time of tensile failure.

The influence of the ratio between elastic and viscous characteristics of epoxy composites is even more reflected in their properties (Table 2) under additional heat treatment (to the main mode 20°C×24 h) at various temperatures (60–140°C). The nature of

the destruction of composite samples upon compression after additional heat treatment (Fig. 2) corresponds to the changes in the energy of their deformation and its components (i.e. the energies of elastic and viscous deformation). When testing the samples after their heat treatment at 60°C, a long plateau after the first threshold is observed which corresponds to plastic deformation practically without an increase in the resistance to deformation. A similar type of fracture under compression was noted when testing samples after heat treatment at 80–100°C.

With an increase in the heat treatment temperature (120°C), the first threshold is rapidly followed by an increase in the deformation resistance to the second threshold of final destruction of the composite, reflecting the loss of plastic deformation and the enhancement of brittleness. A further increase

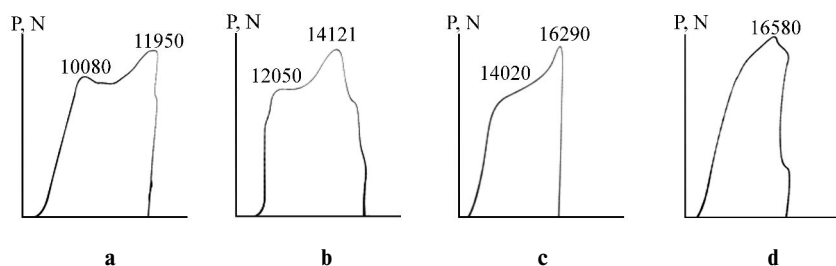


Fig. 2. Diagrams of compression of unfilled epoxy composites on the basis of ED-20 after their heat treatment on the modes: a – without heat treatment; b – 60°C×3 h; c – 120°C×1 h; d – 140°C×1 h

in the heat treatment temperature (140°C) is inexpedient because of the increased fracture in the process of composites after hardening, which leads to a decrease in the dynamic modulus of elasticity, deformation energy, and wear resistance of the composites. The optimum is the optimized (i.e. combined 80+100°C) heat treatment conditions (Table 2, Fig. 3).

The analysis of the X-ray diffraction patterns of samples of epoxy composites (Fig. 3) revealed the effect of heat treatment on the size of the cells formed by the interstitial chains of polymers of the mesh structure. The X-ray diffraction pattern of an epoxy polymer heat-treated at 100°C for 3 hours (Fig. 3, curve 1) manifests two diffusion maxima (as judged from the angular half-width) of different intensities with angular positions ($2\mu\text{m}$) of about 4.0° and 17.6° . According to Bragg's equation, the average distance between two adjacent interstitial sites of the molecular chains of a polymer grid is 2.21 nm and 0.50 nm, respectively, i.e. the mesh size of a polymer grid is 2.21–0.50 nm. Heat treatment at 120°C (Fig. 3, curve 2) does not cause changes in the angular position ($2\Theta_m$) of both diffraction maxima and the distance between two adjacent interstitial sites of molecular chains of the polymer grid. The heat treatment according to the optimized mode (80+100°C) leads to densification of the polymer grid which is testified by the basic shift in the intensity of the amorphous halo in the diffractogram of this sample to the region of larger scattering angles: up to $2\Theta_m=18.2^\circ$ (Fig. 3, curve 3). At the same time,

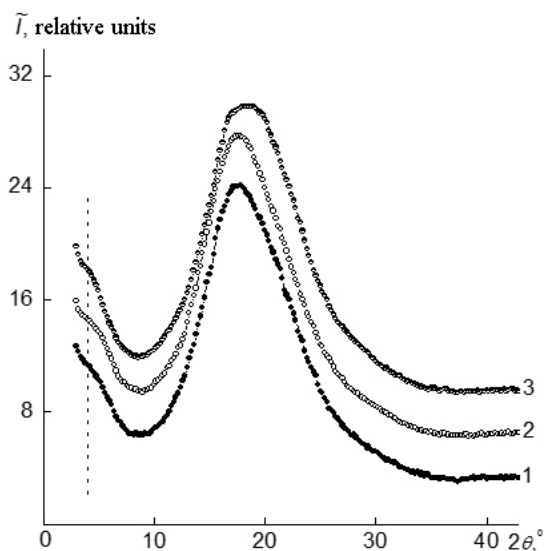


Fig. 3. Wide-angle X-ray diffractograms of the composites on the basis of ED-20 epoxy cured by polyethylene polyamine with a heat treatment during 3 h at different temperatures, °C: 1 – 100; 2 – 120; 3 – 80+100

the distance between two adjacent interstitial sites of molecular chains of the polymer decreases to 0.49 nm.

The analysis of the intensity profiles of small-angle X-ray scattering showed that epoxy composites are structurally homogeneous on the nano-dimensional level, regardless of the heat treatment mode, since there is no contrast of electronic density in their volume.

An increase in the temperature of the heat treatment of epoxy polymers from 60 to 100°C is followed by an increase in the glass transition temperatures (T_g), transition to highly elastic condition (T_e), the modulus of high-elasticity (E_e) which is due to a more complete participation of epoxide groups in the cross-linking reactions and an increase in the cross-linking density (a decrease in the sol fraction and the average molecular mass of interstitial chains (Table 2)).

With an increase in the heat treatment temperature of epoxy polymers from 100 to 120°C and especially to 140°C, a slight decrease (at 120°C) and then a more pronounced decrease in their thermomechanical characteristics are observed, the sol-fraction content and the average molecular mass of interstitial chains increase simabatically. Therefore, the effects of the heat treatment temperature of epoxy polymers in the vitreous (up to 100°C) and highly elastic (120±140°C) states on their thermomechanical properties are different.

Using the developed combined heat treatment of epoxy polymers at temperatures of the polymer in a vitreous state (80°C) and close to the vitrification temperature (100°C) promotes the formation of a more cross-linked structure providing enhanced thermomechanical properties.

Conclusions

The effects of industrial polyamines on the hardening process, the parameters of the three-dimensional structure, the physical-mechanical and viscoelastic properties of epoxy compositions based on a mixture of dianic (ED-20) and aliphatic (DEG-1) epoxy resins have been determined. Taking into account the technological and operational properties of these resins, it is recommended to use Polyamine B for hardening.

The maximum temperature of the exothermic curing reaction of the studied epoxy compositions has been determined, depending on the polyamine hardener used. These values should be taken into account when compiling and adjusting the regimes of preparing the products for structural purposes.

Taking into account the established viscoelastic transition in epoxy composites, it is advisable to heat-

treat them after their curing at 20°C in a vitreous state at the temperatures close to the glass transition temperature in order to achieve their optimal viscoelastic properties under dynamic loading.

The effects of the temperature of additional heat treatment (60–140°C) on the change in thermomechanical properties and the nature of the destruction of epoxy composites have been shown. It was proposed to apply a combined (80+100°C) heat treatment regime.

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ВПЛИВ ПОЛІАМІНІВ НА ВЛАСТИВОСТІ ЕПОКСИДНИХ КОМПОЗИТІВ

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Визначені в'язкопружні властивості композицій на основі епоксидної діанової смоли ЕД-20 в суміші з аліфатичною епоксидною смолою ДЕГ-1 в залежності від застосовуваного промислового поліамінного твердника, додаткового термооброблення (при температурах 60–140°C). Показані відмінності термомеханічних, фізико-механічних властивостей, що виникають внаслідок змін співвідношення енергій пружного та в'язкого деформування. На співвідношення енергій пружного та в'язкого деформування композицій в динамічному режимі напруження впливає сформована просторова структура епоксидної матриці. Показано вплив температури додаткової термообробки на зміну термомеханічних властивостей, характер руйнування епоксидних композицій і запропоновано застосовувати комбінований (80+100°C) режим термооброблення. Для досягнення оптимальних в'язкопружних властивостей одержані епоксидні композиції після отверднення при 20°C доцільно термооброблювати в склоподібному стані при температурах, близьких до температури склування, і використовувати твердник Polyamine B.

Ключові слова: епоксидна смола, поліамінний твердник, зшита структура, в'язкопружні властивості, зносостійкість.

THE INFLUENCE OF POLYAMINES ON THE PROPERTIES OF EPOXY COMPOSITES

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The viscoelastic properties of epoxy resin-based composites ED-20 in a mixture with aliphatic epoxy resin DEG-1 have been determined as functions of the applied industrial polyamine hardener and additional heat treatment (at the temperatures of 60–140°C). The differences in the thermomechanical and physical-mechanical properties, and wear resistance of the composites have been stated resulted from the change in the ratio of the energies of elastic and viscous deformation. The ratio of the energies of elastic and viscous deformation of composites in a dynamic loading mode is influenced by the formed spatial cross-linked structure of the epoxy matrix. The effects of the temperature of additional heat treatment on the change in thermomechanical properties and the nature of the destruction of epoxy composites have been shown. It has been proposed to apply a combined heat treatment conditions (80+100°C). To achieve optimum viscoelastic properties after hardening at 20°C, it is expedient to heat-treat the obtained epoxy composites in a vitreous state at temperatures close to vitrification temperature and use a Polyamine B hardener.

Keywords: epoxy resin; polyamine hardener; cross-linked structure; viscoelastic properties; wear resistance.

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