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REGULAR ARTICLE

Nanomodified Polymer Composite Bandage Systems for Repair of Oil and Gas Pipeline Systems

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The reliability of pipelines in the gas and oil transportation complex is largely determined by corrosion damage and mechanical defects on the external and internal surfaces. The purpose of this study is to develop nanomodified epoxy composite bandage systems with improved thermophysical characteristics for pipeline repair. The studies show that controlled introduction of micro- and nanodispersed fillers into the polymer matrix significantly increases the thermal stability of epoxy composites. In particular, the temperature of the onset of mass loss increases by 47-55 K compared to the unmodified epoxy matrix. It was established that the rational ratio of components (10 wt. % of trimethoprim and 0.050 wt. % of fullerene-carbon black mixture) in the epoxy matrix ensures the formation of a polymer with the maximum value of the activation energy of thermal destruction (E_a = 175 kJ/mol). The improvement of the thermophysical characteristics of the polymer is due to the formation of a hybrid structure, which is realized through the combined action of three mechanisms: the barrier effect of nanofillers, which form a compacted structure and limit the diffusion of oxygen; chemical crosslinking due to the interaction of trimethoprim amino groups with epoxy functional groups; physical interfacial interaction, in particular π–π-interaction with the graphite-like surface of nanoparticles, which leads to a decrease in the segmental mobility of macromolecules and an increase in the energy barriers of the course of thermal destruction processes. The scientific novelty of the work lies in establishing a combined chemical-physical mechanism for stabilizing epoxy composites modified with a bidisperse system of functional fillers, which provides coordinated control over diffusion processes, the polymer network's crosslinking density, and the kinetics of thermal degradation at elevated temperatures. The developed materials exhibit reduced mass loss and increased resistance to thermal-oxidative degradation, confirming their feasibility as highly effective matrices for polymer bandage systems used to repair oil and gas pipelines operating under elevated temperature loads.

Keywords: Nanomodified epoxy composites, Pipeline repair, Polymeric bandage systems, Thermal stability, Thermogravimetric analysis, Thermal destruction kinetics, Activation energy, Physical interaction, Chemical interaction.

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1. INTRODUCTION

1.1 Statement of the Problem

Pipeline transport is a key component of energy infrastructure, ensuring the continuous transportation of oil and natural gas, which are critically important for industry and society. A significant portion of the main pipelines operates beyond their design service life, leading to the accumulation of various defects, including corrosion damage, cracks, mechanical deformations, and defects in welded joints. The development of such damage reduces the strength and integrity of pipelines, increases the risk of failures, and results in significant economic and environmental consequences [1-4]. In this context, technologies for repairing pipelines without interrupting the transportation of energy resources are of particular importance, as they ensure process continuity and reduce operating costs. One of the most effective and technologically feasible approaches is the application of polymer composite bandage systems. These systems consist of composite repair structures and polymeric binding materials designed to localize defects, redistribute stresses in damaged zones, restore load-bearing capacity and sealing performance, and enhance the durability of pipeline sections by forming an external reinforcing shell without the need for complex welding operations.

Currently, polymer composite bandage systems based on epoxy matrices are widely used due to their high adhesion to metal substrates, corrosion resistance, and ease of application. A promising approach to improving their performance is the modification of the epoxy matrix with nanodispersed fillers, which promote the formation of a denser polymer structure, reduce diffusion permeability to aggressive media, and enhance the mechanical and

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thermal properties of the material. Thus, the development of nanomodified polymer composite bandage systems for the repair of oil and gas pipelines is a relevant scientific and applied task aimed at improving the reliability of pipeline systems, reducing failure rates, and minimizing environmental risks during operation [5-7].

1.2 Analysis of Recent Research and Publications

According to recent studies [8], the use of functional epoxy nanocomposites enhances the anticorrosion performance of materials by up to 50 % and reduces the wear rate by up to 40 % [9, 10]. This improvement is attributed not only to the mechanical reinforcement of the epoxy matrix but also to the formation of a hierarchical barrier structure that hinders the diffusion of aggressive species (water, oxygen, chloride ions, and sulfates) to the metal surface. The incorporation of carbon nanoparticles at concentrations of 0.5-1.0 wt. % results in a significant increase in composite strength (by 25-40 %) and elastic modulus (up to 20 %), as well as improved fracture toughness due to crack propagation inhibition, crack deflection and branching, and energy dissipation at the matrix-nanofiller interface [11-14]. At the micro- and nanoscale levels, these particles act as nucleation and structuring centers, leading to densification of the polymer network and a reduction in free volume available for the penetration of aggressive media. In addition, the formation of so-called "labyrinth-like" structures increases the effective diffusion path length, thereby reducing mass transport rates within the material. Furthermore, an increase in adhesion strength by 30-40 % has been reported with the addition of nanoparticles [14, 15]. This effect is attributed to enhanced interfacial interactions and the possible formation of physicochemical bonds between the functional groups of the epoxy oligomer and the nanofiller surface. High adhesion strength is a critical parameter for ensuring the long-term performance of bandage systems, as it determines resistance to delamination under cyclic mechanical and thermal loading. In addition, the incorporation of nanodispersed carbon fillers improves the thermal stability of the composite by restricting segmental mobility of macromolecular chains and stabilizing the polymer structure [15-20]. Collectively, these effects promote the formation of a dense and structurally stable polymer matrix with enhanced barrier properties. Such materials demonstrate improved performance under cyclic thermal loading conditions, which is particularly important for pipelines transporting heated media or operating in harsh climatic environments.

The aim of this work is to enhance the efficiency of pipeline repair technologies by developing nanomodified polymer composite bandage systems with improved thermophysical performance for oil and gas pipeline applications.

2. MATERIALS AND RESEARCH METHODS

For the preparation of polymer materials intended for bandage systems, the following components were used: an epoxy oligomer ED-20 as the binder (ISO 18280:2010) and polyethylene polyamine (PEPA) as the curing agent (TU 6-05-241-202-78), with a component ratio (%) of ED-20 : PEPA = 100 : 10 by weight.

To improve the performance characteristics of the composite materials, the following modifiers were introduced: a biocidal filler, trimethoprim ($C_{14}H_{18}N_4O_3$, CAS: 738-70-5), which is a synthetic antibiotic capable of inhibiting the growth of microorganisms and bacteria (particle size: 5-10 μm), and a nanodispersed fullerene–carbon black mixture (NFCM), which acts as a structural nanomodifier of the epoxy matrix. The incorporation of NFCM promotes the formation of a dense crosslinked polymer network, resulting in enhanced mechanical strength and improved thermophysical properties (particle size: 30-40 nm).

The technology for forming epoxy composites was carried out in a specific sequence, as described in the works [5, 8].

Thermal stability was evaluated using thermogravimetric analysis (TGA) and differential thermal analysis (DTA) performed on a "Thermoscan-2" derivatograph [18].

The activation energy of thermal degradation was determined by mathematical processing of TGA data using the Broido method [16].

3. DISCUSSION OF RESEARCH RESULTS

Bandage repair of pipelines in oil and gas transportation systems involves the installation of a composite reinforcing structure on the damaged section of a pipeline. This structure redistributes stresses, reduces stress concentration in the defect zone, and restores sealing integrity. Particular attention is paid to the polymer material used as the matrix of the bandage system, as it governs adhesion to the metal substrate, load transfer capability, and the long-term durability of the repair structure. One of the key criteria for selecting the polymer matrix is its thermal stability, which ensures the retention of mechanical, physical, and barrier properties over the operational temperature range of the pipeline. Adequate thermal stability prevents thermally induced degradation, loss of adhesion, and the formation of defects within the repaired zone. To evaluate the thermal stability and determine the operating temperature range of the polymer matrix used in the bandage system, thermogravimetric analysis (TGA) and differential thermal analysis (DTA) were employed. These methods enable the assessment of thermal transformation processes in the developed materials and the determination of their allowable service temperature limits. The obtained data are essential for predicting the service life of epoxy composites under variable thermal loading conditions.

Based on the comprehensive analysis of the experimental results, it was established that the maximum operating temperature of the protective coating modified with a nanodispersed fullerene–carbon black mixture should not exceed 555 K. Similarly, the maximum operating temperature of the coating modified with the biocidal filler trimethoprim should not exceed 550 K.

It was assumed that the introduction into the volume of epoxy oligomer ED-20 of two functional fillers at the

same time – nanodispersed fullerene-carbon black mixture (NFCM) and trimethoprim (TMP) will provide a synergistic effect in the form of increased heat resistance and stable operation of epoxy composites intended for the repair of pipelines of the gas and oil transportation complex. Thus, based on the generalization of the results of mathematical modeling [20], which establish the quantitative dependences of "composition-structure-properties" of the polymer system, a scientifically substantiated selection of three epoxy compositions with different ingredient contents for further research was carried out, in particular:

PM 1 – epoxy oligomer ED-20 – 100 wt. %; hardener polyethylenepolyamine PEPA – 10 wt. %; dispersed filler (5…10 μm) trimethoprim $C_{14}H_{18}N_4O_3$ – 5.0 wt. %; nanodispersed fullerene-carbon black mixture (30…40 nm) – 0.050 wt. %;

PM 2 – epoxy oligomer ED-20 – 100 wt. %; hardener polyethylenepolyamine PEPA – 10 wt. %; dispersed filler (5…10 μm) trimethoprim $C_{14}H_{18}N_4O_3$ – 10.0 wt. %; nanodispersed fullerene-carbon black mixture (30…40 nm) – 0.050 wt. %;

PM 3 – epoxy oligomer ED-20 – 100 wt. %; hardener polyethylenepolyamine PEPA – 10 wt. %; dispersed filler (5…10 μm) trimethoprim $C_{14}H_{18}N_4O_3$ – 15.0 wt. %; nanodispersed fullerene-carbon black mixture (30…40 nm) – 0.050 wt. %.

According to thermogravimetric analysis (Fig. 1, Table 1), the incorporation of differently dispersed fillers (PM1–PM3) resulted in an increase in the initial mass loss temperature (T_0) from 587 K for the unmodified epoxy matrix to 634-642 K for the developed epoxy composite coatings. Thus, the T_0 value increased by approximately 47-55 K compared to the unfilled matrix.

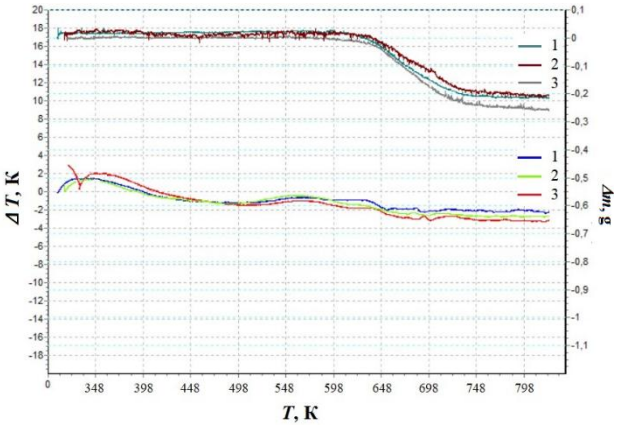

Fig. 1 – Results of thermogravimetric (TGA) and differential thermal analysis (DTA) of composites containing a two-component filler: (1) PM1 (5.0 wt. % TMP + 0.050 wt. % NFCM); (2) PM2 (10.0 wt. % TMP + 0.050 wt. % NFCM); (3) PM3 (15.0 wt. % TMP + 0.050 wt. % NFCM)

The obtained results indicate a high structural stability of the polymer network, which can be attributed to two main factors: physical and chemical interactions.

(i) Physical interactions. Trimethoprim contains two benzene rings with delocalized π-electrons, while the nanodispersed fullerene–carbon black mixture (NFCM) represents an amorphous graphitic carbon material possessing a π-electron system similar to that of graphene fragments or fullerenes. The adsorption of trimethoprim on the NFCM surface via π–π stackings interactions between its aromatic rings and the graphitic surface of the nanoparticles leads to the formation of an interconnected network of physical bonds. These interactions act as bridge-like linkages between the polymer matrix and the filler, resulting in increased cohesive strength of the epoxy composite due to restricted mobility of polymer chains and their segments.

(ii) Chemical interactions. Trimethoprim can interact with reactive groups of the epoxy matrix, as confirmed by wide-angle X-ray diffraction (WAXD), as well as with secondary hydroxyl groups formed during polymerization. These interactions are likely to proceed via nucleophilic addition mechanisms involving electron-donating nitrogen atoms of trimethoprim, which may participate in post-curing reactions of the epoxy network. Such processes promote additional intermolecular bonding and partial immobilization of flexible –CH_2– segments of the polymer chains. As a result, segmental mobility decreases, leading to suppression of thermo-oxidative degradation through a reduction in the number of reactive sites and stabilization of the molecular architecture of the composite.

From a thermodynamic perspective, the formation of additional intermolecular interactions reduces the configurational entropy of the system by limiting the degrees of freedom of polymer chain segments. This structural ordering introduces a kinetic barrier to the initiation and propagation of thermal degradation processes, which is reflected in an increase in the activation energy of thermodestruction.

Furthermore, it was established that for the developed composites at the temperature T_f (714-753 K), the relative mass loss (ε_m) ranges from 54 % to 67 %, which is 13-36 % lower than that of the unmodified epoxy matrix. This indicates effective inhibition of thermal degradation processes and improved structural integrity of the polymer under thermal loading.

Table 1 – Results of thermogravimetric analysis (TGA)

Composition of polymer composites (wt.%)	T_0, K	T_5, K	T_{10}, K	T_{20}, K	T_f, K	ε_m, %
Epoxy matrix	587	616	625	641	714	80
PM with a TMP content of 15.0 wt. %.	609	624	640	652	740	69
PM with a NFCM content of 0.050 wt.%.	605	620	642	653	733	58
PM 1: with a TMP content of 5.0 wt. %. + NFCM content of 0.050 wt. %.	634	642	658	671	745	67
PM 2: with a TMP content of 10.0 wt. %. + NFCM content of 0.050 wt. %.	642	648	659	672	753	54
PM 3: with a TMP content of 15.0 wt. %. + NFCM content of 0.050 wt. %.	603	616	629	641	737	84

Differential thermal analysis (DTA). On the DTA curves (Fig. 1, Table 2), we observed a shift in the temperature of the onset of the exoeffect from T_{init} = 460 K to T_{init} = 503-518 K. An increase in the initial temperature of the exoeffect by 43-58 K compared to the unfilled matrix and by 30-45 K, compared to the developed polymers containing a single filler, indicates a slowdown in thermal

destruction due to the complex strengthening of the structure.

From a thermodynamic perspective, the interaction of trimethoprim with the fullerene–carbon black mixture and the polymer matrix can be interpreted as the formation of coordination-stabilized complexes and hydrogen-bonded networks. In particular, the amino groups of trimethoprim can interact with the functional groups of the epoxy oligomer and form hydrogen bonds with hydroxyl (–OH) groups generated during epoxy ring opening [21-25]. However, an increase in trimethoprim content (particularly in PM3) leads to a reduction in thermophysical properties compared to PM1–PM2. This effect is attributed to spatial–structural (topological) constraints associated with the aggregation of trimethoprim particles at higher concentrations. As a result, a decrease in the onset temperature of the exothermic effect (T_{init} = 488 K) is observed, approaching values characteristic of composites modified with a single functional filler.

Table 2 – Results of differential thermal analysis (DTA)

Composition of polymer composites (wt.%)	Temperature Intervals of Exoeffects				Maximal Temperature Exoeffects, T_{max}, K
	T_{init}, K	T_f', K	ΔT_1, K	ΔT_2, K	
Epoxy matrix	440	659	199	3.05	518
PM with a TMP content of 15.0 wt. %.	488	663	175	1.54	550
PM with a NFCM content of 0.050 wt. %.	473	670	160	1.59	555
PM 1: with a TMP content of 5.0 wt. %. + NFCM content of 0.050 wt. %.	503	692	189	1.35	565
PM 2: with a TMP content of 10.0 wt. %. + NFCM content of 0.050 wt. %.	518	694	176	1.59	568
PM 3: with a TMP content of 15.0 wt. %. + NFCM content of 0.050 wt. %.	488	662	174	1.54	562

To determine the operating temperature range of the epoxy composites, the Broido method was applied [14, 16]. This method is based on thermogravimetric analysis (TGA) and involves a graphical–analytical approach to evaluating the activation energy (E_a) of thermal degradation processes. The method involves constructing a linear relationship between the logarithmic function of the residual mass fraction and the reciprocal temperature ($1/T$). The activation energy is then determined from the slope of the resulting straight line (tg φ) according to the Broido equation (1).

$$-\mathrm{tg}(\varphi) = y_i/x_i, \quad (1)$$

The mass loss data for the investigated polymer systems (PM1–PM3) were obtained from TGA measurements (Table 3). These data were subsequently converted to relative mass-loss values (%) using Equation (2), which accounts for the initial and residual sample masses at each temperature point.

$$(100 - \Delta\mathrm{m})\% = \left(100 - \left(\frac{\mathrm{m_{in}} + \Delta\mathrm{m}}{\Delta\mathrm{m}} \cdot 100\right)\right)\%, \quad (2)$$

where m_{in} – sample mass at the temperature (T_1 = 573 K = const); Δm – mass of the polymer as the temperature increases.

To calculate the activation energy for the thermal degradation of the epoxy composites, the experimental data were processed using a graphical–analytical approach by fitting the thermogravimetric data to a logarithmic function of mass loss (Table 4). This approach enables linearization of the TGA data and facilitates the determination of kinetic parameters of the degradation process. In particular, the dependence of the logarithm of the residual mass fraction on the reciprocal temperature was constructed, allowing the activation energy (E_a) to be determined from the slope of the corresponding linear fit using the Broido method.

Table 3 – Mass loss of the studied epoxy composites determined from TGA curves

T, K	PM 1		PM 2		PM 3	
	g	$(100 - \Delta m)$, %	g	$(100 - \Delta m)$, %	g	$(100 - \Delta m)$, %
573	0.025	– 7.10	0.019	– 5.40	– 0.006	1.70
583	0.020	– 5.68	0.017	– 4.83	– 0.010	2.84
593	0.015	– 4.24	0.013	– 3.69	– 0.013	3.69
603	0.010	– 2.84	0.010	– 2.84	– 0.017	4.83
613	0.005	– 1.42	0.005	– 1.42	– 0.025	7.10
623	– 0.005	1.42	– 0.001	0.28	– 0.042	11.93
633	– 0.025	7.10	– 0.015	4.26	– 0.069	19.60
643	– 0.045	12.78	– 0.025	7.10	– 0.095	26.99
653	– 0.085	24.15	– 0.045	12.78	– 0.123	34.94
663	– 0.105	29.83	– 0.065	18.47	– 0.149	42.33
673	– 0.119	33.81	– 0.085	24.15	– 0.175	49.72
683	– 0.138	39.20	– 0.101	28.69	– 0.199	56.53
693	– 0.161	45.74	– 0.125	35.51	– 0.216	61.36
703	– 0.199	56.53	– 0.134	38.07	– 0.225	63.92
713	– 0.200	56.82	– 0.159	45.17	– 0.238	67.61

The application of this method provides a reliable evaluation of the energy barrier associated with thermal degradation and allows for comparison of the thermal stability of the studied composites with different compositions. The obtained kinetic parameters characterize the polymer's resistance to thermal degradation and are essential for predicting its behavior at elevated temperatures.

Table 4 – Calculated values of the logarithm of the residual mass fraction of epoxy composites

T, K	$10^3/T$, K^{-1}	ln [100/(100 – Δm)]		
		PM 1	PM 2	PM 3
573	1.745	–	–	– 4.063
583	1.715	–	–	– 3.547
593	1.686	–	–	– 3.280
603	1.658	–	–	– 3.006
613	1.631	–	–	– 2.608
623	1.605	– 4.247	– 5.862	– 2.063
633	1.580	– 2.608	– 3.134	– 1.522
643	1.555	– 1.989	– 2.608	– 1.157
653	1.531	– 1.286	– 1.989	– 0.844
663	1.508	– 1.038	– 1.589	– 0.597
673	1.486	– 0.885	– 1.286	– 0.375
683	1.464	– 0.698	– 1.084	– 0.182
693	1.443	– 0.492	– 0.824	– 0.050

703	1.422	– 0.182	– 0.736	0.019
713	1.403	– 0.175	– 0.509	0.120

The activation energy of thermal degradation was evaluated using Equation (3), where the slope (tan φ) was obtained from the linear approximation of the graphical dependence (Fig. 2) in accordance with Equation (1).

$$E_a = -R\,\mathrm{tg}(\varphi) \qquad (3)$$

The slope of this dependence reflects the rate of mass loss as a function of temperature and allows the kinetic parameters of the degradation process to be quantified. The negative sign indicates that the mass of the sample decreases with increasing temperature.

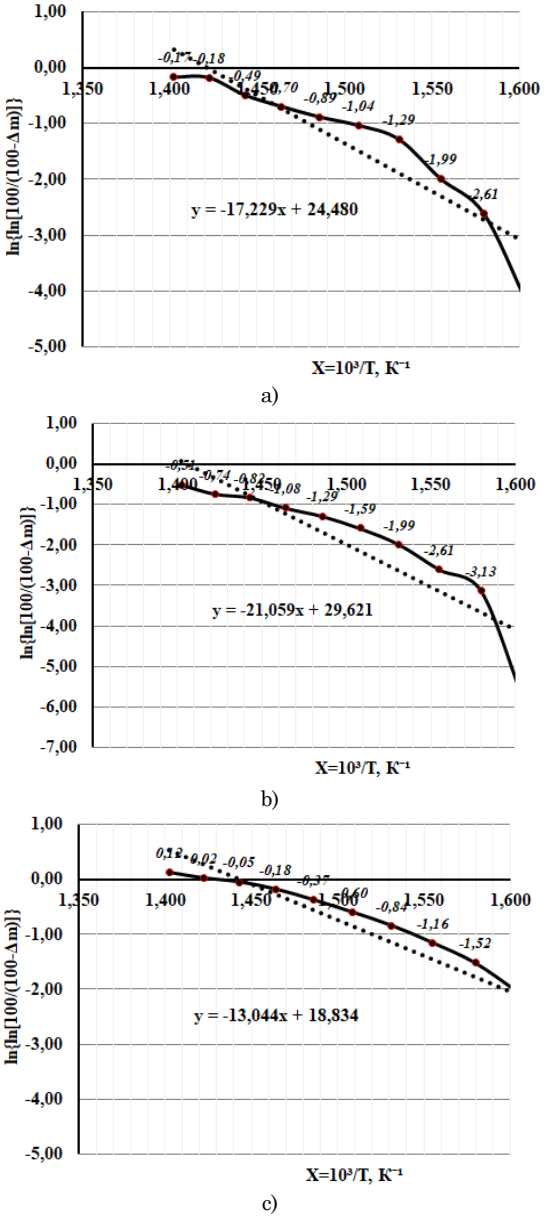

Fig. 2 – Logarithmic dependence of the residual mass fraction on reciprocal temperature ($10^3/T$, K^{-1}) during thermal degradation of epoxy composites: (a) PM1; (b) PM2; (c) PM3

The obtained activation energies provide insight into the thermal stability of the studied epoxy composites. Higher E_a values correspond to greater resistance of the polymer structure to thermal degradation, indicating a more stable, densely crosslinked network. Conversely, lower activation energies suggest facilitated degradation processes associated with increased molecular mobility or structural heterogeneity in the material.

Based on the mathematical processing of the experimental data (Table 5), it was established that PM2 exhibits the highest activation energy among the studied materials (E_a = 175 kJ/mol). This result indicates a retardation of thermal degradation of the epoxy composite due to modification with a functional filler at an optimal composition.

Table 5 – Calculated activation energy values for thermal degradation of epoxy composites

Composition of polymer composites (wt.%)	X_H	X_k	Y_H	Y_k	$tq_{(\varphi)}$	Energy Activation E_a, kJ/mol
PM 1: with a TMP content of 5.0 wt. %. + NFCM content of 0.050 wt. %.	1.6	1.4	17.2	24.4	17.2	145
PM 2: with a TMP content of 10.0 wt. %. + NFCM content of 0.050 wt. %.	1.6	1.4	21.0	29.6	21.0	175
PM 3: with a TMP content of 15.0 wt. %. + NFCM content of 0.050 wt. %.	1.7	1.4	13.0	18.8	13.0	108

Based on a comprehensive analysis of thermogravimetric (TGA) and differential thermal analysis (DTA) data, a mechanism for enhancing the thermal stability of the developed epoxy composite modified with a nanodispersed fullerene–carbon black mixture (NFCM) and trimethoprim has been established. The incorporation of the nanodispersed carbon filler leads to the formation of a percolation-like barrier structure that significantly hinders the diffusion of oxygen and volatile degradation products. This effect is reflected in a shift of the onset temperature of thermal decomposition (T_0) toward higher values and a reduction in the mass loss rate. In addition, an increase in the temperature corresponding to the maximum decomposition rate (T_{max}) is observed, indicating suppression of thermo-oxidative degradation processes.

Modification of the polymer matrix with trimethoprim increases the effective crosslink density and restricts the segmental mobility of macromolecules, as evidenced by an increase in the glass transition temperature. This behavior is attributed to both the chemical interaction of the amino groups of trimethoprim with epoxy groups of the matrix and the formation of π–π stacking interactions with the graphitic surface of the nanoparticles. As a result, a hybrid network forms, combining covalent and physical (intermolecular) bonds, thereby increasing the energy barrier to polymer degradation.

Kinetic analysis of the thermal degradation process

reveals an increase in the effective activation energy (E_a) for the main decomposition stages, indicating a more complex degradation mechanism and enhanced stabilization of the polymer matrix. This finding is consistent with a reduced rate of volatile product evolution and an increased residual mass fraction (ε_m) at elevated temperatures, suggesting the formation of a more thermally stable structure.

Thus, the improvement in thermal stability of the developed composite is achieved through the synergistic action of three key mechanisms:

(i) the barrier effect of the nanodispersed filler, which limits mass transport;

(ii) an increase in the crosslink density of the polymer network due to chemical modification;

(iii) the formation of additional physical interfacial interactions that raise the activation energy of thermal degradation. The combined effect of these factors shifts the onset of mass loss to higher temperatures and enhances the overall thermal stability of the material, thereby improving its suitability for applications under elevated thermal loads.

The combined effect of these factors shifts the initial temperature of mass loss into the high-temperature region and increases the material's thermal stability, thereby improving its suitability for use under elevated temperature loads.

4. CONCLUSIONS

Based on comprehensive research, the following results were obtained:

1. Based on thermogravimetric (TGA) and differential thermal analysis (DTA) of the developed polymer materials used as matrices in bandage systems, it was established that the incorporation of trimethoprim into the epoxy oligomer ED-20 at a content of 10 parts by weight, together with a nanodispersed fullerene–carbon black mixture (0.050 parts by weight), results in an increase in the thermal stability of the coatings, in particular, an increase in the onset temperature of thermal degradation by 47-55 K compared to the unfilled epoxy matrix. The enhancement of thermophysical properties is attributed to the combined effect of (i) chemical interactions (additional crosslinking via amino groups of trimethoprim), (ii) physical adsorption through π–π stacking interactions between aromatic fragments of trimethoprim and the surface of the nanofiller, and (iii) the barrier effect of nanoparticles, which hinder oxygen diffusion and promote more uniform dissipation of thermal energy.

2. Based on the calculated activation energy, it was established that epoxy composites containing trimethoprim (10 wt.%) and a nanodispersed fullerene–carbon black mixture (0.050 wt.%) exhibit the highest energy barrier to thermal degradation among the studied materials. The activation energy value (E_a = 175 kJ/mol) serves as a reliable indicator of the durability of the polymer material used as the matrix of the bandage system under long-term operation at elevated temperatures.

3. The mechanism of enhanced thermal stability has been substantiated, elucidating the influence of the constituent components (trimethoprim and the nanodispersed fullerene–carbon black mixture) on the thermal degradation behavior of the developed polymer used as the matrix of the bandage system. The proposed mechanism is based on comprehensive experimental results and summarizes the processes occurring during thermal exposure of the polymer. In particular, the nanodispersed fullerene–carbon black mixture forms a barrier network that effectively hinders oxygen diffusion into the polymer matrix, thereby suppressing thermo-oxidative degradation. Simultaneously, trimethoprim contributes to both physical modification (π–π stacking interactions with the nanophase) and chemical modification (through reactions with epoxy groups), resulting in additional crosslinking and reduced segmental mobility of polymer chains. The synergistic effect of these functional fillers promotes the formation of a structurally stable polymer network with enhanced thermal stability. This confirms the feasibility of applying the developed materials for the repair of oil and gas pipelines, particularly under elevated thermal loading conditions.

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Наномодифіковані полімерні композитні бандажні системи для ремонту трубопроводів газо-нафтотранспортного комплексу

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Надійність трубопроводів газо-нафтотранспортного комплексу значною мірою визначається наявністю корозійних ушкоджень і механічних дефектів зовнішніх та внутрішніх поверхонь. Метою даного дослідження є розроблення наномодифікованих епоксидних композитних бандажних систем із покращеними теплофізичними характеристиками для ремонту трубопроводів. Результати досліджень свідчать, що регульоване введення в полімерну матрицю мікро- та нанодисперсних наповнювачів забезпечує суттєве підвищення термічної стабільності епоксидних композитів. Зокрема, температура початку втрати маси зростає на 47-55 К порівняно з немодифікованою епоксидною матрицею. Встановлено, що раціональне співвідношення компонентів (10 мас.ч. триметоприму та 0,050 мас.ч. фулерено-сажової суміші) у епоксидній матриці забезпечує формування полімеру з максимальним значенням енергії активації термічної деструкції (E_a = 175 кДж/моль). Покращення теплофізичних характеристик полімеру зумовлене формуванням гібридної структури, що реалізується через сукупну дію трьох механізмів: бар'єрного ефекту нанонаповнювачів, які формують ущільнену структуру та обмежують дифузію кисню; хімічного зшивання внаслідок взаємодії аміногруп триметоприму з епоксидними функціональними групами; фізичної міжфазової взаємодії, зокрема π–π-взаємодії з графітоподібною поверхнею наночасток, що призводить до зниження сегментальної рухливості макромолекул і підвищення енергетичних бар'єрів перебігу процесів термічної деструкції. Наукова новизна роботи полягає у встановленні поєднаного хіміко-фізичного механізму стабілізації епоксидних композитів, модифікованих бідисперсною системою функціональних наповнювачів, який забезпечує узгоджене керування дифузійними процесами, щільністю зшивання полімерної сітки та кінетикою термічної деструкції в умовах підвищених температур. Розроблені матеріали характеризуються зниженням втрати маси та підвищеною стійкістю до термоокислювальної деструкції, що підтверджує їхню доцільність використання як високоефективних матриць у полімерних бандажних системах для ремонту нафто- та газопроводів, які експлуатуються в умовах підвищених температурних навантажень.

Ключові слова: Наномодифіковані епоксидні композити, Ремонт трубопроводів, Полімерні бандажні системи, Термостійкість, Термогравіметричний аналіз, Кінетика термічної деструкції, Енергія активації, Фізична взаємодія, Хімічна взаємодія.