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Basic approaches and requirements for the design of tribological polymer composite materials with high-modulus fillers

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Abstract

Based on a combination of a system-oriented approach and a synergetic concept, the requirements for the design of tribological polymer composite materials with high-modulus fillers are formed. These materials are considered as an open dynamic system that evolves during operation. The principles of the synergetic concept for tribotechnical systems taking into account the theory of evolution and self-organization to ensure its self-governing and self-supporting development are considered. It is revealed that in the process of interaction of elements of the tribosystem the cooperation of local areas of their materials is formed with the emergence of a critical number of such areas and the creation of an information field about their functioning. The direction of self-organization of processes and states of parts materials in the tribotechnical system and expediency of using the conclusions of the synergetic concept in the construction of polymer composite materials, as well as their nonequilibrium are shown. The issues of creation of tribophysical bases of wear resistance of tribotechnical systems with conjugations of the details made or strengthened by polymeric composite materials are considered. Polymer composite materials are considered as a set of interacting ensembles of local areas, the principle of maximum wear resistance (reliability) is used. Tribological principles and requirements to creation and substantiation of expediency and efficiency of use of high-modulus fillers in polymers are formulated.

Key words: polymer composite material, high-modulus filler, tribotechnical system, system-oriented approach, synergetic concept

Introduction

The use of parts made of polymer composites and restored by coating these materials has shown their effectiveness in increasing the durability of systems and units of machines. However, there is a problem of optimizing the composition of polymer composites, the content of fillers, their distribution in the polymer matrix. Poorly developed issues of modification of the matrix and fillers of polymeric composite materials (PCM) by flows of matter and physical fields [1, 2].

In [2-5] it was shown that under some conditions of friction the structure of the heterogeneous PCM material, which corresponds to the Sharpy principles, is not optimal. Heterogeneous materials of PCM applied on the surface of machine parts must have high wear resistance, thermal stability of phases, the ability to adjust the morphology of the structure and the direction of its elements. Their efficiency has been insufficiently studied due to significant differences in views on the impact of structural features of PCM and the lack of data on the combination of components in a set of characteristics and their properties. There are no generalized criteria for selecting optimal wear resistance compositions. It is possible to increase the wear resistance of PCM by improving their structure, the optimal combination of characteristics and properties of components, the implementation of processes and the state of self-organization.

Literature review

Along with extensive studies of the processes of friction and wear of materials with homogeneous and microheterogeneous structure [5], the mechanism of wear of PCM with micro- and macroheterogeneous structure with high-modulus filler is insufficient [6]. In the works of V.Ya. Belousova [3], I.M. Borodina [7], V.I. Savulyak [8], V.V. Aulina, [9], I.M. Fedorchenko [10], N.P. Suh [11-13], M.F. Ashby [14] and others, it is noted that from a number of known types of composite materials PKM is the most promising. In terms of the formation of new, wear-resistant PKM and coatings, it is advisable to proceed from the estimated estimates of optimization of the structure, content size and distribution of high-modulus fillers, the characteristics of their materials. The complexity and versatility of PCM wear processes, according to VP Bondarenko, VV Aulina, VI Savulyak and other authors, forces to introduce empirical constants and phenomenological functions that have no real analogues, or to create simplified models of friction surfaces and schemes of wear mechanism [4, 15, 16].

The connection between the wear process of PCM and their mechanical properties is given in [6, 17]. The results of PCM wear resistance studies with homogeneous and heterogeneous structure show that in the first case it is lower than in the second due to faster equalization of contact pressure. The phenomenon of spontaneous installation and maintenance of stationary wear and tear mode of PCM is also due to the existence of feedback. Based on the ideal conditions of sliding contact, in [6] with the help of friction surface models, the tribotechnical characteristics of PCM with different structure and different composition were calculated.

The approach to solving the problem of managing the properties of PCM is of considerable interest and requires innovative developments in the direction of analytical research on ways to improve wear resistance and optimal selection of conjugate surfaces of parts. Since there is no mathematical or physical model that takes into account all the features of the process of friction and wear of PCM today, it is necessary to conduct an analytical study of the dependence of wear resistance on the structure and complex properties of components and PCM in general. Varying the content of the components of PCM, with their unchanging nature, change the total contact pressure of the composition and its structure [18-21], providing the required level of properties that affect wear resistance.

It is revealed that in the conditions of friction and wear elastic and plastic deformations are the main processes that initiate the emergence and development of physical, chemical and mechanical processes in the surface layers of PCM [4, 15]. It is shown that in PCM the main share of loading is received by a filler. Reinforcing fillers prevent the movement of dislocations in the matrix, which is subject to plastic deformation, limiting it [15]. At the same time it is strengthened by increasing the content of filler and reducing the distance between its particles. In [3, 8] it was found that depending on the structural state of the PCM, the magnitude of the accumulated plastic deformation is not the same, which causes different processes of relaxation processes. The type and dispersion of filler particles (carbides, borides, oxides, intermetallics) in the polymer matrix, which are barriers to plastic deformation, significantly affect the inhibition of the relaxation process, but it is not known how the degree of dispersion of the filler affects the properties of PCM, filler – for stress relaxation and wear process.

E.A. Adirovich and D.I. Blokhintsev [22] proposed a dynamic approach to the study of friction and wear of materials, which was further developed in the works of S.V. Krysova [23] and other scientists [24, 25]. The material in the friction zone is considered as a system of excited oscillators that are attenuated in accordance with the relaxation properties, and the assumption is made about the possibility of energy dissipation by wave fluxes [24, 23]. This is one of the manifestations of structural self-organization of PCM and a method of increasing their wear resistance.

L.J. Bershadsky [26-28] proposed information-dynamic and structural-dynamic concepts, in which friction is considered as a stochastic system of linear oscillators (elementary excitations), as synergistic effects (autosynchronization, autowave parameters, etc.) due to the flow correlation of these excitations. These concepts continue to evolve.

In the thermodynamic approach to friction [29, 30], quasi-static and kinetic friction are considered and generalized principles of designing the material of parts with a given wear resistance are proposed: the principle of rheodynamic localization; the principle of dissipative heterogeneity; the principle of triboshielding.

In the synergetic approach [31-34] it is important to use the synergetic concept in friction and wear, which determines the conditions of processes and formation of states of self-organization of surface layers during running, operation and technological processing of parts, especially in strengthening, restoration and modification. In this case, the triad coupling of parts must have minimal wear, and therefore maximum wear resistance, which deserves special attention.

Analysis of approaches to the study of the ability of materials of PCM components to resist wear [35-38] indicates the need to combine the physical nature of the set of processes and states with their tribological interpretation. In this regard, it is advisable to interpret and solve the problem of increasing the wear resistance of PCM from a tribophysical point of view, including: a set of characteristics and properties of their surface layers, interaction with the working (technological) environment, development of rational and optimal methods of process and state management PCM during hardening and modification and operation [39]. This problem is extremely relevant in tribology and tribology. To solve it, a combination of a system-oriented approach and a synergetic concept in the study of processes, states and functioning of PCM in different operating conditions and their computer modeling is proposed.

Purpose

The aim of this work is to elucidate the possibilities of a system-oriented approach and synergetic concept of designing tribological polymer composite materials with high-modulus fillers and developing a system of requirements for them.

Results

The system-oriented approach involves consideration of conjugations of parts operating in working (technological) environments of tribotechnical system, consisting of interacting parts of components, systems and units of machines, working (technological) environment, structure, characteristics and properties of PCM materials and wear and tear change over time. Since the process of development of any tribotechnical system of machines must be considered from a systemic point of view, only a system-oriented approach makes it possible to understand the nature of irreversible changes that occur in the PCM. The principle of symmetry [40-42], according to which the properties and relationships of system elements are determined, is formulated as a law in the composition of scientific theories as a methodological principle. In this sense, the principle of symmetry can be understood as a generalization of the principles of relativity and invariance [43]. The dialectical relationship of simple and complex in the tribotechnical system with PCM is manifested in the fact that the structure of the materials of the matrix and filler changes during operation. In this case, such a system should be considered from a dynamic point of view, ie with the emergence of complexity [40-44].

The basis of the synergetic concept of research conditions and mechanisms for implementing processes and states of different types of self-organization PMK and working (technological) environment in the tribotechnical system is a set of interrelated principles, which is that changing the structure, characteristics and properties of component materials occurs due to the collective interaction of their components and physical fields.

The principles of the synergetic concept are mainly methodological principles, to which the following requirements apply: the relation of ring causality is observed; their number is limited; mappings of space of processes and states and the theory of dynamic systems are used [45-47]. In identifying the relationship between these principles, it is advisable to use their development in mathematical, logical and philosophical aspects [48], and any evolutionary process in the tribotechnical system can be represented as changes in conditional states of order and chaos, combined processes and phase transitions (PhT) in materials of details and working (technological) environments.

In essence, the synergetic concept contains the principles of subordination and compliance, selection and Kozma Prutkov, which are relevant to the means of observation. At the same time, observability emphasizes the limitations and relativity of ideas about the studied tribotechnical system and means the relativity of interpretations to its scale, initial and expected results and makes the system open to methodological and systematic interpretations, combining synergetic concept with system-oriented approach. On the other hand, the problem of interpreting the tribotechnical system is similar to the problem of identification and is characterized by the fact that collective interactions do not change its total energy, but redistribute between elements: conjugate parts and working (technological) environment.

The theory of evolution and self-organization teaches the art of soft control systems: weak influences that are resonant, extremely effective and must meet the internal trends of tribotechnical systems. The main problem is how to push the tribotechnical system on one of the own and favorable ways with small resonant action, providing self-managing and self-supporting development. This applies, first of all, to the structures of PCM parts and working (technological) environment, which are implemented in a complex tribotechnical system through the influence of resonant. Their evolution itself is contradictory, as it consists of both orderly and unregulated processes, but is subject to the law of harmony, the content of which reflects the concept of "golden section" [40, 44, 49]. If the regularities of changes in the structure of PCM in tribotechnical systems allow several equally probable states, then the one that corresponds to the minimum entropy is realized. Other features of the evolution of systems are associated with the emergence of a new type of structure. This is preceded by an increase in fluctuations at the macro level, the development of entropy exports to the environment and the transition from the old dissipative structures to new secondary structures in the materials [50].

In the process of interaction of the elements of the tribotechnical system reveal the cooperation (collective action, coherence) of their local areas, the emergence of a critical number of such areas and the creation of a single information field about their functioning. The complex of selectively involved local regions takes the form of mutual assistance in obtaining a useful result in the tribotechnical system [51]. In this case, the principle and theory of evolutionism [52-54] of systems does not contradict the two great theories of evolution of L. Boltzmann and Charles Darwin. The idea of selection plays an important role in it: the new arises as a result of the selection of the most effective forms, and inefficient innovations are rejected by the development process. This emphasizes the most important pattern of systems: the focus of their development to improve structural organization, ie, self-organization, self-development [53-56]. Today, the idea of evolutionism is a regulatory principle that focuses on identifying specific patterns of evolution of tribotechnical systems at all its structural levels (macro-, meso-, micro-, nano-) and stages of self-organization. In this regard, the principle of "Razor Okkami" is a measure of thrift or the law of economy [44].

The central place in the main synergetic principle is given to the principle of self-organization, which is that the internal activity of the tribotechnical system is opposed to the disorganizing element of entropy and, under certain conditions, leads to self-motion. This determines the following methodological direction of self-organization of processes and states in the tribotechnical system:

– processes and states must be irreversible;

– the system is open and remote from the state of thermodynamic equilibrium;

– entropy produced in the system does not accumulate in it, but is excreted, from the external environment there is a flow of negentropy;

– in nonequilibrium systems fluctuations accumulate and amplify and obey the principle of positive feedback;

– the process of different types of self-organization begins at the micro and nanoscale with local areas of system elements and the intensification of fluctuations under the influence of external influences;

– as a result of increasing fluctuations, the system becomes more unstable, the previous order and structure are destroyed and qualitatively new ones appear when energy is dissipated into the external environment;

– the emergence of a new order occurs spontaneously at the time of extreme instability, when the materials of the elements of the system acquire significant coherence;

– the development of the system is a nonlinear process, and therefore can be described by a nonlinear differential equation;

– characteristics and properties of materials of elements of the system have a probabilistic nature and randomness has a significant impact on their further development;

– any qualitative transition and the emergence of a new order in the system are associated with the bifurcation point (choice of path of development);

– an adequate description of the development of the tribotechnical system involves taking into account its prehistory, etc.

This indicates that the processes and states of self-organization, as a positive result of evolution, occur due to intrinsic tribotechnical systems, which are based on two mutually exclusive trends: the establishment of a certain order and the emergence of self-organization and the formation of a new structure; in the course of further development the previous order is destroyed, and the relationships between the local regions of the materials of the elements are subject to change with the spontaneous establishment of a new order and the emergence of new dissipative and secondary structures.

The analysis of processes of development of tribotechnical systems during running-in and operation testifies to expediency of use thus conclusions of the synergetic concept:

– self-organization reveals the process of development of various forms of systems;

– any development process can be carried out in open systems;

– the existence of self-organization confirms the principle of self-movement and internal activity of the materials of the elements;

– the openness of the system is an insufficient condition for its self-organization, as there is a need for a state remote from thermodynamic equilibrium;

– at each stage of development of the system self-organization acquires specific features: the higher the evolutionary system, the greater the requirements for the conditions of implementation of self-organization and more complex processes and states;

– the source and initial moment of development of the system associated with the emergence of a new, is the emergence of a set of coincidences;

– fluctuations or random deviations direct the development of nonequilibrium systems with the gradual accumulation and intensification of fluctuations;

– irreversibility, instability and nonequilibrium – the most fundamental properties of systems than stability and equilibrium, etc.

According to the theory of nonequilibrium processes [51, 57-59], the properties of tribotechnical systems remote from the equilibrium state become unstable and their return to the initial state is optional. However, their behavior is ambiguous, but there are effects of coordination, correcting the behavior of elements at macroscopic distances and time intervals [60]. Cooperatively coordinated behavior determines the processes of ordering, the emergence of certain structures out of chaos, their transformation and complication [60]. The greater the deviation from equilibrium, the greater the coverage of correlations and relationships, the higher the consistency of processes characterized by nonlinearity and the presence of positive and negative feedback [63, 64], and the possibility of control over the tribotechnical system.

In the process of evolution, the external contribution to the total entropy of a tribotechnical system can be arbitrary, depending on the parameters of the external environment and the nature of its interaction with the system. There are two types of situations [65]:

– total entropy decreases due to its return through the boundary surface:

$$dS/dt < 0 ; \qquad \Phi_S < \sigma_S , \tag{1}$$

– total entropy is constant and maximum for these conditions of operation of the tribotechnical system, but less than the entropy of equilibrium:

$$S_{\max} = \text{const} < S_{рівн.\max} . \tag{2}$$

When the entropy flux is equal to its production ($\Phi_S = \sigma_S$), the tribotechnical system is in a stable steady state or a state of current equilibrium. If the internal entropy $d_iS > 0$, then the energy processes in the system are always dissipative, ie accompanied by a decrease and scattering of energy. Energy dissipation is the main sign of current equilibrium, but, in accordance with the principle of self-permeability of equilibrium, the system can not get out of it spontaneously and under external influence intensified processes to compensate, like the manifestation of electromagnetic induction [24, 25]. According to the principle of minimum entropy production, the laws of nature [66] suggest several options for the development process (organization), and the one that meets the minimum energy dissipation is realized. In this case, the driving force of the processes of self-organization of materials of the elements of the tribotechnical system is the PhT or their sequence, resulting in a transition to a more ordered state, corresponding to the lower symmetry.

Among the extreme principles of the synergetic concept and one of the key provisions of modern physics, including and tribophysics is the principle of stationary or least action (PLA) [40]: among all possible movements (directions of development) of elements and systems in general is realized that for which the minimum is the product of energy consumed at the time of action. The principle makes it possible to obtain the equation of motion of the system using the stationary value of a special functional - action [40, 67].

The combination of system-oriented approach and synergetic concept, as an integrative search for patterns in tribology PCM, allows to take into account the results of research on improving wear resistance, as well as a set of properties and characteristics of materials triboelements, working (technological) environments, friction and wear in tribotechnical system.

Creation of tribophysical bases of wear resistance of tribotechnical systems, with conjugated details, made or strengthened by PCM, using the system-oriented approach and synergetic concept, has independent, methodological and scientific value as allows to specify subject idea of wear resistance and to expand information on processes in materials. working (technological) environment, on the limits of their interaction and the evolution of states. In essence, the tribophysical direction in mechanical engineering confirms the implementation of a new mechanism of friction based on the effect of self-organization. Unlike known methods, concepts and approaches, this methodology makes it possible to establish the relationship of various process parameters, state and material properties of parts from a tribophysical point of view.

The kinetics of the exchange process of interaction of ensembles of local regions of PCM is described by the stochastic differential equation:

$$dx_j^i / dt = f_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right) - g_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right), \tag{3}$$

where $f_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right)$, $g_{ij}\left(x_1^i, x_2^i, ..., x_n^i\right)$ is the functions of the rate of accumulation and scattering of internal energy. For a simplified consideration of the functioning of the local regions of the PCM, we believe that the transition of the state of the ensemble ε_i to ε_e causes an almost instantaneous change in the state of the triboelement material. Analysis of the structural organization of the PCM was performed using integer functions:

$$N(t) = \left[N_1(t), N_2(t), ...N_i(t), ..., N_n(t)\right], \tag{4}$$

where $N_i(t)$ is the number of identical ensembles ε_i at each moment of time t. The structural entropy and the probabilistic state are equal to:

$$S_c(P_\alpha) = -\sum_{i=1}^{n} P_{ci} \cdot \ln P_{ci} ; \qquad P_{ci}(t) = N_i(t) \Big/ \sum_{i=1}^{n} N_i(t) . \tag{5}$$

In such conditions of operation of PCM it is possible to use the principle of the maximum wear resistance (reliability) [68, 69] according to which conjugation of details, working in the working (technological) environment, tries to minimize the interaction with it. The measure of such interaction is the deviation of the parameters of tribotechnical systems from the optimal values, which is consistent with the principle of structural adaptability, formulated by B.I. Kostecki, L.I. Bershadsky, V.G. Kanarchuk, M.A. Boucher in the works [70-72]. The principle of maximum wear resistance (reliability) is special in the dynamics of structural adaptability of triboelement materials (conjugations of parts, parts and working (technological) environment), and dynamic equilibrium in tribotechnical systems as a whole obeys the principle of least action [40]. The equation of the entropy balance of the local region of the PCM has the form:

$$\bar{\rho}_{\partial i}(dS_i/dT_i) + divS_i = \xi(S_i)\,, \tag{6}$$

where dS_i/dT_i, $divS_i$, $\xi(S_i)$, $\bar{\rho}_{\partial i}$ are the inflow, outflow, entropy growth and average density of defects in the *i*-th local region.

Since the rate of destruction in local areas of PKM is controlled by the rate of entropy production, to maintain the state of quasi-wear of the surface layers of parts it is necessary to maintain its saturation with vacancies, ensure high density of mobile and reduce the density of stationary dislocations. Based on modern ideas of the theory of friction and wear in the works of V.A. Bieloho, V.Ia. Bielousova, D.M. Harkunova, B.I. Kostetskoho, I.V. Krahelskoho, A.P. Semenova, I.M. Fedorchenka, V.P. Bondarenka, V.V. Aulina, V.I. Savuliaka, etc., it is possible to formulate a number of tribological principles of creation and substantiation of expediency and efficiency of use of PCM with high-modular fillers:

– the structure of PCM should be heterogeneous and consist of solid fillers (inclusions), evenly distributed in the polymeric elastic-plastic matrix;

– the structure of the PCM should not change significantly during friction, but can be rebuilt into a more favorable structure without weakening;

– the layer of PKM applied to the surface of the part must have less strength than the layers below (positive gradient rule);

– under the influence of working (technological) or external environments in PCM there should be no significant structural changes, deterioration of characteristics of durability and plasticity;

– it is recommended to include high-modulus substances and substances capable of working as a solid lubricant in the PCM;

– there must be an adhesive bond between the structural components of the PCM;

– anti-emergency additives introduced into the friction zone should not significantly reduce the strength of PCM;

– coefficients of friction of solid fillers (inclusions) among themselves and on the material of the PCM matrix should be minimal, etc.

Note that the requirements for the structure and properties of wear-resistant PCM can be clarified and specified in the process of experimental and theoretical studies depending on the type of mating parts, friction conditions and type of wear: minimizing porosity; providing a heterogeneous structure of the material with a uniform distribution of the filler in the elastic-plastic matrix; the adhesive bond between the components must be strong enough. Ideal, in terms of tribotechnical requirements, is the three-phase structure of PCM: elastic-plastic matrix, solid wear-resistant high-modulus fillers (inclusions) and solid lubricant particles to ensure the implementation of the rule of positive gradient of properties.

The analysis of operational characteristics of PCM of tribotechnical appointment shows that they are defined by conditions of work of tribocoupling of details and in wide limits vary: low values of coefficient of friction and high wear resistance; combination of optimum volume and surface strength with easy hardness of surfaces of conjugated details and sufficient viscosity to exclude brittle fracture; high fatigue strength; ability to form layers of secondary structures; sufficient thermal conductivity and optimal values of the coefficient of thermal expansion (CTE); availability of solid or liquid lubricants; economy and manufacturability in the manufacture.

The change in the mechanical properties of the materials of the surface layers of PCM parts is due to the reduction of free surface energy and, as a consequence, the reduction of work required to increase the surface, revealed mechanisms for converting mechanical energy into other forms of energy.

This makes it possible to make some generalizations that can be used to increase the wear resistance of parts made of PCM:

– mechanical methods of activation radically affect the reactivity of the surface layers of the materials of parts;

– mechanical activation is a method of directed regulation of physical, physicochemical and tribological properties of working surfaces and surface layers of parts;

– under the influence of mechanical activation there are qualitative and quantitative changes in the nature of chemical bonds and the transformation of chemical compositions of the surface layers of parts;

– mechanochemical methods of activation stimulate the development of heterogeneous reactions in the near-surface layers.

Conclusions

1. The methodology of combining a system-oriented approach and a synergetic concept in the design of polymer composite materials for the manufacture of couplings of parts, systems and units of machines and coatings is formulated.

2. In the system-oriented approach, polymer composite materials are considered as systems with components: matrix, high-modulus fillers, additives of particles of solid ink materials.

3. It is found out that the basic synergetic concept of research of conditions and mechanisms of realization of processes and states of various types of self-organization of polymeric composite materials and working (technological) environment in tribotechnical system.

4. The set of principles contained in the synergetic concept is considered: subordination and conformity, choice, etc. The expediency of using the conclusions of the synergetic concept in the construction of polymer composite materials is clarified.

5. The use of the theory of evolution and self-organization of materials of the tribotechnical system, conditions of providing self-managing and self-supporting its development are considered.

6. Based on the principle of self-organization of elements in the tribotechnical system, the methodological orientation of self-organization of different types, processes and states of polymeric composite materials with high-modulus filler is revealed.

7. Since nonequilibrium processes are observed in the friction and wear of conjugated parts in the tribotechnical system, the theory of nonequilibrium processes should be taken into account when designing polymer composite materials, taking into account the evolution of materials and the effects of matching and correcting their behavior.

8. From the theoretical point of view, the nature of entropy change in the tribotechnical system, energy dissipation, the extreme principle of synergetic concept and the principle of stationary or nonlinear action are considered.

9. Polymer composite material is considered as a set of interacting ensembles of local areas. The analysis of their structural organization is performed using an integer function taking into account the structural entropy and probabilistic state. In the conditions of operation of polymer composite material it is possible to use the principle of maximum wear resistance (reliability), according to which the conjugation of parts, assemblies, units of machines operating in the working (technological) environment minimizes its interaction with it.

10. A number of tribological principles of creation and substantiation of expediency and efficiency of use of polymeric composite materials and requirements to their structure and properties are formulated. Generalizations are made which can be used at increase of wear resistance of the details made of polymeric composite materials.

References

1. Aleksandrov E.E., Kravets I.A., Lyisikov E.P. i dr. (2006) Povyishenie resursa tehnicheskih sistem putyom ispolzovaniya elektricheskih i magnitnyih poley: monografiya. [H.: NTU "HPI"]. – 544 s.

2. Devoyko O.G., Kardapolova M.A. (2003) Sozdanie kompozitsionnyih pokryitiy na osnove smesey s ispolzovaniem lazernogo nagreva [Sb.nauch.rabot PGTU. – Novopolotsk]. – S.141-144.

3 Beloysov V.Ya. (1984) Dolgovechnost detaley mashin s kompozitsionnyimi materialami [Lviv: Vyshcha shkola]. – 180 s.

4. Malikov I.I., Ivanov V.D., Kotyagov L.F. i dr. (1985) Vliyanie kompozitsionnyih pokryitiy na kachestvo prirabotki i iznosostoykost truschihsya sopryazheniy avtotraktornyih dvigateley [Trenie i iznos, 1985. – T. VI, № 1]. – S. 125-132.

5. Vanin G.A. (1985) Mikromehanika kompozitsionnyih materialov: monografiya [K.: Nauk. dumka]. – 304s.

6. Bondarenko V.P. (1987) Tribotehnicheskie kompozityi s vyisokomodulnyimi napolnitelyami [K.: Nauk. dumka]. – 232 s.

7. Borodin I.N. (1982) Uprochnenie detaley kompozitsionnyimi pokryitiyami [M.: Mashinostroenie]. – 141 s.

8. Savuliak V.I. (2004) Naukovi zasady formuvannia na splavakh zaliza kompozytsiinykh metalokarbidnykh shariv zi stabilnymy strukturamy ta pidvyshchenymy trybotekhnichnymy kharakterystykamy [avtoref. dys... d-ra tekhn. nauk: 05.02.01]. – 39 s.

9. Aulin V.V. Trybofizychni osnovy pidvyshchennia znosostiikosti detalei ta robochykh orhaniv silskohospodarskoi tekhniky [avtoref. dys. ... d-ra tekhn. nauk : 05.02.04]. – 36 s.

10. Fedorchenko I.M. (1980) Kompozitsionnyie spechennyie antifriktsionnyie materialyi [K.: Naukova dumka]. – 404 s.

11. Suh N.P. (1978) The delamination theory of wear [Wear, Vol.1]. – P1-162.

12. Suh N.P. (1975) The delamination theory of wear [Massachusetts Institute of Technology]. – 158p.

13. Suh N.P. (1973) The delamination theory of wear [Wear, Vol.25 - №1973]. – P 11-124.

14. Ashby M.F., Jones D.R.H. (1996) Engineering Materials [Oxford: Butterworth-Heinemann]. – 322p.

15. Kanovich M.Z., Trofimov N.N. (2003) Soprotivlenie kompozitsionnyih materialov: monografiya [M.: Mir]. – 504 s.

16. Kompozitsionnyie materialyi. Spravochnik (1985) / Pod red. D.M. Karpinosa [K.: Naukova dumka]. – 592 s.

17. Sorokov S. (2003) Klasternyi pidkhid do rozrakhunku fizychnykh kharakterystyk kompozytnykh materialiv [Lviv: In-t fizyky kondens. system NANU]. – 23 s.
18. Gerland Dzh. (1976) Razrushenie kompozitov s dispersnyimi chastitsami v metallicheskoy matritse. Kompozitsionnyie materialyi [M.:Mir] S.105-130.
19. Ivanochkin P.G. (2009) Kontaktnyie zadachi dlya uzlov treniya s dvuhsloynyimi kompozitsiyami tribotehnicheskogo naznacheniya [avtoref. diss. na soisk. uch. stepeni d-ra tehn. nauk.: spets.01.02.04, 05.02.04]. – 38s.
20. Pribyitkov G.A. (2002) Mezhfaznyiy massoperenos na granitse metallov i tugoplavkih soedineniy s metallicheskimi rasplavami i ego rol v formirovanii strukturyi kompozitsionnyih materialov i pokryitiy [avtoref. diss. na soiskanie uchenoy stepeni d-ra. tehn. nauk: spets. 05.16.01]. – 40 s.
21. Sokolovskaya E.M., Guzey L.S. (1978) Fizikohimiya kompozitsionnyih materialov [M.: Mosk. un-ta] – 256 s.
22. Adirovich E., Blohkhinzev D. (1943) On the Forces of Dry Friction. [J.Phys. USSR. - 1943, V 7, №1] – P.29-36.
23. Kryisov S.V. (1992) Volnovyie protsessyi pri kontaktnyih vzaimodeystviyah podvizhnyih sopryazheniy v uprugih elementah mashin i konstruktsiy [avtoref. dis. nauk. stepeni kand. fiz.-mat. nauk: spets. 01.02.06]. – 23s.
24. Boroday A.V. (2007) O protsessah samoinduktsii v tribosistemah [Trenie i smazka v mashinah i mehanizmah. – M.: Mashinostroenie. – № 2]. – S. 3-10.
25. Boroday A.V., Klimenko A.V., Ponomarev V.I. (2005) O friktsionnom vzaimodeystvii tel kak induktsionnom i tunnelnom protsesse [Izv. vuzov. Sev. – Kavk. region. Tehn. nauki. Spetsvyip. Problemyi triboelektrohimii]. – S. 36-42.
26. Bershadskiy L.I. (1981) Samoorganizatsiya i nadezhnost tribosistem [Kiev]. – 35 s.
27. Bershadskiy L.I. (1982) Osnovyi teorii strukturnoy prisposablivaemosti i perehodnyih sostoyaniy tribosistem i ee prilozhenie k zadacham povyisheniya nadezhnosti zubchatyih i chervyachnyih peredach [Dis. ... d-ra tehn. nauk]. – K. – 328 s.
28. Bershadskiy L.I. (1990) Strukturnaya termodinamika tribosistem [K.: Znanie]. – 30 s.
29. Klementev N.M. (1971) Termodinamika treniya [Voronezh: Voronezhsk. politehi, in-t]. – 305s.
30. Praca naukowo_badawcza. Laboratoryjne i eksploatacyjne badania teflonowego SLIDER 2000. WSI w Radomiu. Radom. 1993. – 36p.
31. Andrianov I.V., Barantsev R.G., Manevich L.I. (2004) Asimptoticheskaya matematika i sinergetika: put k tselostnoy prostote [M.: Editorial URSS] – 304 s.
32. Gershman I.S. (2009) Sinergetika protsessov treniya [Trenie, iznos, smazka. T.12, №40]. – S.1-8.
33. Ershov S.V. (1993) Sinergetika. Novyie napravleniya. Nelineynyie volnyi [Fizika i astrofizika. – M.: Nauka]. – S. 306–319.
34. Knyazeva E.N., Kurdyumov S.P. (2002) Osnovaniya sinergetiki. Sinergeticheskoe mirovidenie [SPb.: "Aleteyya"]. – 414 s.
35. Kostetskiy B.I. (1976) Poverhnostnaya prochnost materialov pri trenii [Kiev: Tehnika] – 296 s.
36. Kostetskiy B.I. (1981) Fundamentalnyie zakonomernosti treniya i iznosa [Kiev: Znanie] – 31 s.
37. Kragelskiy I.V. (1968) Trenie i iznos [M.:Mashinostroenie]. – 480 s.
38. Lyubarskiy I.M., Palatnik L.S. (1976) Metallofizika treniya [M.: Metallurgiya]. – 176 s.
39. Naydyish V.M. (2004) Kontseptsii sovremennogo estestvoznaniya [M.: Alfa – M; INFRA-M]. – 622s.
40. Aulin V.V. (2014) Fizychni osnovy protsesiv i staniv samoorhanizatsii v trybotekhnichnykh systemakh: monohrafiia [Kirovohrad: Vyd. Lysenko V.F.]. – 370 s.
41. Butkovskiy O.Ya. (1996) Narushenie simmetrii pri byistryih bifurkatsionnyih perehodah [zhurn. eksperim. i teoret. fiziki. T.109, Vyip. 6]. – S. 2201–2207.
42. Dorodnitsyin V.A., Elenin G.G. (1988) Simmetriya nelineynyih yavleniy. Kompyuteryi i nelineynyie yavleniya. Informatika i sovremennoe estestvoznanie. [M.: Nauka]. – S. 123–191.
43. Uhtomskiy D.A. (2002) Dominanta. Stati raznyih let [SPb.: Piter]. – 448 s.
44. Printsipyi samoorganizatsii. Per. s angl. A.Ya. Lernera (1966) [M.:Mir]. – 621 s.
45. Katok A.B., Hasselblat B. (2005) Vvedenie v sovremennuyu teoriyu dinamicheskih sistem [M.: Faktorial]. – 767 s.
46. Koronovskiy A.A., Trubetskov D.I. (2002) Nelineynaya dinamika v deystvii [Saratov: Gos. UNTs "Kolledzh"]. – 324 s.
47. Preobrazhenskiy N.G. (1993) Dinamika razvitiya fiziki neravnovesnyih sistem [Edinstvo fiziki. – Novosibirsk: Nauka]. – S. 158–174.
48. Budanov V.G. (2006) O metodologii sinergetiki [Voprosyi filosofii. – № 5]. – S. 79-94.
49. Soroko E.M. (2006) Zolotyie secheniya, protsessyi samoorganizatsii i evolyutsii sistem: Vvedenie v obschuyu teoriyu garmonii sistem [M.: KomKniga]. – 264 s.
50. Glensdorf P., Prigozhin I. (2003) Termodinamicheskaya teoriya strukturyi, ustoychivosti i fluktuatsiy [M.: URSS]. – 280 s.

51. Nikolis G., Prigozhin I. (1979) Samoorganizatsiya v neravnovesnyih sistemah. Ot dissipativnyih struktur k uporyadochennosti cherez fluktuatsii: monografiya [M.: Mir]. – 512 s.

52. Эбелинг В., Энгель А., Файстель Р. Физика процессов эволюции. Синергетический подход [М.: Эдиториал УРСС]. – 328 с.

53. Aulin V.V. (2010) Zahalni zakonomirnosti evoliutsii ta samoorhanizatsii v trybosystemakh [Suchasni problemy trybolohii: Tezy dopovidei Mizhnar. nauk.-tekhn. konf. – K.:IVTs ALKON NAN Ukrainy]. – S.94.

54. Aulin V.V. (2011) Fizychni osnovy evoliutsii staniv trybosystem ta protsesiv samoorhanizatsii yikh elementiv [Zb. m-liv mizhnar. nauk.-prakt. konf. "Olviiskyi forum - 2011", 8-12 chervnia 2011 – Yalta]. – S.14-15.

55. Aulin V.V. (2012) Osnovni synerhetychni komponenty proiavu riznykh form samoorhanizatsii v trybotekhnichnykh systemakh [Zb. m-liv mizhnar. nauk.-prakt. konf. "Olviiskyi forum-2012", 6-10 chervnia 2012, – Yalta., t. 12]. – S.60-62.

56. Aulin V.V. (2014) Systemno-spriamovanyi pidkhid ta synerhetychna kontseptsiia realizatsii protsesiv i staniv samoorhanizatsii materialiv elementiv, robochykh ta tekhnolohichnykh seredovyshch trybotekhnichnykh system [Zb. nauk. prats KNTU/ Tekhnika v s/h vyrobnytstvi, haluzeve mashynobud., avtomatyzatsiia, vyp. 27. – Kirovohrad]. – S.78-87.

57. Nikolis G., Prigozhin I. (1979) Samoorganizatsiya neravnovesnyih sistem: monografiya [M.: Mir]. – 635 s.

58. Pelyuhova E.B., Fradkin E.E. (1997) Samoorganizatsiya fizicheskih sistem [SPb.: SPbGU]. – 324 s.

59. Polak L.S., Mihaylov A.S. (1983) Samoorganizatsiya v neravnovesnyih fiziko-himicheskih sistemah [M.: Nauka]. – 285 s.

60. Prigozhin I.R., Konderudi D. (2002) Sovremennaya termodinamika. Ot teplovyih dvigateley do dissipativnyih struktur [M.: Mir] – 319 s.

61. Stratonovich R.L. (1985) Nelineynaya neravnovesnaya termodinamika [M.: Nauka]. – 480 s.

62. Skott E. (2007) Nelineynaya nauka: rozhdenie i razvitie kogerentnyih struktur [M.: Fizmatlit]. – 560s.

63. Emelyanov S.V., Korovin S.K. (1997) Novyie tipyi obratnoy svyazi: upravlenie pri neopredelennosti [M.: Nauka]. – 352 s.

64. Tverdohlebov V.A. (2009) Nelineynost kak dominanta Prirodyi [Rossiyskiy himicheskiy zhurnal. – T.LIII, № 6] – S.3-6.

65. Dulesov A.S., Semenova M.Yu., Hrustalev V.I. (2011) Svoystva entropii tehnicheskoy sistemyi [Fundamentalnyie issledovaniya. – №8]. – S. 631-636.

66. Prangishvili I.V. (2003) Entropiynyie i drugie sistemnyie zakonomernosti. Voprosyi upravleniya slozhnyimi sistemami [M.: Nauka]. – 428 s.

67. Korolkov B.P. (2011) Termodinamicheskie osnovyi samoorganizatsii: monografiya [Irkutsk: IrGUPS]. – 120 s.

68. Aulin V.V. (2009) Pidvyshchennia nadiinosti trybosystem realizatsiieiu protsesiv samoorhanizatsii [M-ly III mizhnar. nauk.-tekhn. konf.: "Suchasni problemy trybotekhniky", 7-9 zhovtnia 2009r. – Mykolaiv: NUK].-S 15-17.

69. Kuzmenko A.G. (2011) Nadezhnost uzlov treniya po prochnosti i iznosu [Hmelnitskiy:HNU].–391s.

70. Bushe N.A. (2003) Rol neobratimyih protsessov v sovmestimosti tribosistem [Zheleznyie dorogi mira. – №2]. – S.38-41.

71. Kanarchuk V.E. (1986) Adaptatsiya materialov k dinamicheskim vozdeystviyam [Kiev: Naukova dumka]. – 264 s.

72. Костецкий Б.И., Зазимко О.В., Зелинский А.М. (1986) Расчет интенсивности изнашивания при нормальном трении [В кн.: Применение новых материалов, заменителей и систем смазки в узлах трения машин и оборудования – Воронеж, 1986. – С.35-38.

Аулін В.В., Гриньків А.В., Смаль В.В., Лисенко С.В., Пашинський М.В., Катеринич С.Е, Лівіцький О.М. Основні підходи та вимоги до конструювання трибологічних полімерних композитних матеріалів з високомодульними наповнювачами

В роботі на основі поєднання системно-спрямованого підходу і синергетичної концепції сформовані вимоги до конструювання трибологічних полімерних композитних матеріалів з високомодульними наповнювачами. Ці матеріали розглядаються як відкрита динамічна система, яка еволюційно розвивається в процесі експлуатації. Розглянуті принципи синергетичної концепції для триботехнічних систем з урахуванням теорії еволюції і самоорганізації для забезпечення її самокеруючого і самопідтримуючого розвитку. Виявлено, що в процесі взаємодії елементів трибосистеми формується кооперативність локальних областей їх матеріалів з виникненням критичного числа таких областей й створення інформаційного поля про їх функціонування. Показано спрямованість самоорганізації процесів і станів матеріалів деталей в триботехнічній системі та доцільність використання висновків синергетичної концепції при конструюванні полімерних композитних матеріалів, а також їх нерівноважність. Розглянуті питання створення трибофізичних основ зносостійкості триботехнічних систем зі спряженнями деталей, виготовлених або зміцнених полімерними композитними матеріалами. Полімерні композитні матеріали розглянуті як сукупність взаємодіючих ансамблів локальних областей використано принцип максимальної зносостійкості (надійності). Сформульовані трибологічні принципи та вимоги до створення і обґрунтування доцільності і ефективності використання високомодульних наповнювачів в полімерах.

Ключові слова: полімерний композитний матеріал, високомодульний наповнювач, триботехнічна система, системно-спрямований підхід, синергетична концепція