MACHINE BUILDING. PROCESS METALLURGY. MATERIALS SCIENCE

МАШИНОБУДУВАННЯ. ТЕХНОЛОГІЯ МЕТАЛІВ. МАТЕРІАЛОЗНАВСТВО

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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF HEATING PROCESSES IN RUBBER-CORD COMPOSITE UNDER CYCLIC DEFORMATION

О.О. Ларін, Ю.А. Вязовиченко. **Розрахунково-експериментальне дослідження закономірностей нагріву гумокордного композиту при циклічному деформуванні.** Композиційні матеріали, зокрема еластоміри, знаходять широке використання у сучасному машинобудуванні. Суттєвою особливістю таких матеріалів є їх в'язкопружні властивості, прояв яких супроводжується вивільненням енергії у вигляді тепла. Процес самонагріву спричиняє загальне підвищення температури, яке сприяє зміні механічних властивостей матеріалу, викликає додатковий термонапружений стан. Все це істотно впливає на міцність конструкцій, сприяє прискоренню процесів старіння і деградації і, зрештою, суттєво зменшує ресурс. Мета роботи полягає в визначені закономірностей формування теплового стану гумокордних композитів шляхом чисельного моделювання з використанням даних, отриманих в ході експериментальних досліджень за різних умов циклічного навантаження. Чисельне моделювання задачі конвективної теплопровідності проводилось на основі методу скінчених елементів. Експериментальні дослідження проводились засобами сучасного вимірювального комплексу INSTRON/E3000. В ході роботи були отримані якісні і кількісні залежності петлі гістерезису від часу, що утворились при циклічному деформуванні гумокордного композиту. Отримано картини розподілу температури по зразку, а також характер нагріву аж до моменту стабілізації. Встановлено залежність температури само нагріву від амплітуди деформування і частоти навантаження.
Ключові слова: гумокордний композит, самонагрів, петлі гістерезису, циклічне деформування

O.O. Larin, Y.A. Viazovychenko. **Numerical and experimental investigation of heating processes in rubber-cord composite under cyclic deformation.** Composite materials such as elastomers, are widely used in modern engineering. An essential feature of such materials is their viscoelasticity. It's accompanied with the release of energy as a heat. The self-heating process leads to rising of temperature, which causes the mechanical properties changing. That significantly influences on the strength of designs, accelerates the aging and degradation processes and significantly reduces a design life. Aim deals with the identification of the regularities of thermal state of rubber-cord composites by numerical simulation using data which was obtained experimentally at different conditions of cyclic loading. Numerical modeling of heat-transfer problem was carried out using finite element method; the experimental studies were carried out by using of modern measuring complex INSTRON/E3000. The qualitative and quantitative regularities of hysteresis loops that were formed during cyclic deformation of rubber-cord composite depending on time were obtained during the research. As a result of the numerical simulation of convective heat transfer problem the temperature distribution pattern of the specimen were obtained. Heating curves were also obtained in dependence of temperature on strain amplitudes and the frequency of loading. Comparison of the results that were obtained in the experiment and in numerical simulation shows a good convergence.
Keywords: Rubber-cord composite, self-heating, hysteresis loop, cyclic deformation

Introduction. Elastomeric materials used in the automotive and aviation industries are often subjected to cyclic loading with a significant amplitude of deformation and frequency. This can lead to the release of heat, and, depending on the external cooling conditions, leads to a significant change in temperature [1, 2].

An increase in the temperature of rubber and rubber composites contributes to the prolongation of the process of their vulcanization (clay, embrittlement). This causes a significant change in mechanical properties [3] and greatly accelerates the processes of aging and degradation [4], and thus reduces the reliability of the design and its resource [4, 5].

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Heat emission during cyclic deformation of rubber-like materials is due to their significant visco-elasticity. Indeed, for re-loading in these materials, a loop of hysteresis is formed on the deformation curve, which corresponds to the amount of energy emitted in the form of heat. Prolonged cyclic heat generation forms a non-stationary process of its accumulation and causes a significant increase in temperature [6].

In the operating conditions of real machine building structures, the nature of the load has a complex time dependence, so the stress-strain state (SSS) is also difficult. This leads to heterogeneity of the temperature distribution, causes the appearance of additional thermal deformations and thermal stresses, causes heterogeneity in the distribution of material properties and characteristics of their durability.

Therefore, the problem of determining the temperature field, which is formed with a prolonged dynamic load of elastomers and their composites, is an actual scientific and practical task, the solution of which requires the development of theoretical methods and the conduct of experimental tests.

Formulation of the problem. In this paper, an algorithm for numerical simulation of a non-stationary process of self-heating rubber-composite composites caused by their cyclic deformation is proposed. In this algorithm, it is assumed that the amount of heat that has been formed corresponds to the area of the hysteresis loops at each point of the design. The following is proposed to solve the problem of non-stationary thermal conductivity at a temperature quasigarmonic load.

The purpose of the work is to determine the regularities of the formation of the thermal state of rubber composites by numerical simulation using data obtained during experimental studies.

Achieving this goal is associated with solving the following problems.

Conduct an experimental study to determine visco-elastic characteristics of a composite material consisting of a rubber matrix and a unidirectional textile cord.

Numerical simulation of the process of self-heating of this type of materials.

Estimation of the reliability of the proposed mathematical model.

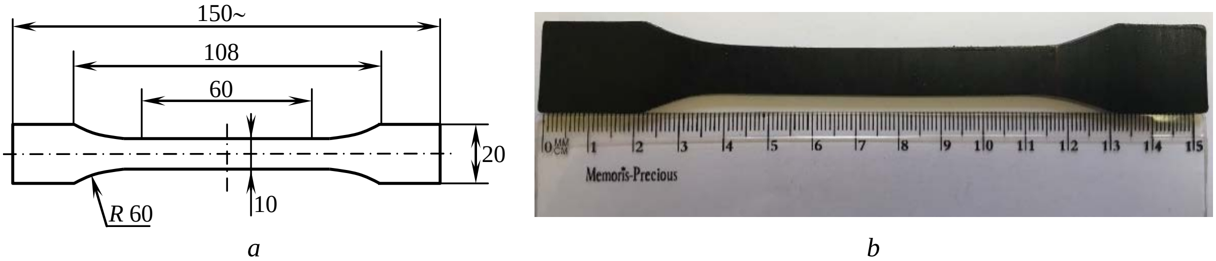
The object of research – the processes of self-heating occurring in rubber-composite structural elements during their cyclic deformation.

Materials and methods. An important part of the simulation of such processes is the preliminary determination of the patterns of hysteresis loops formation in the dynamic loading of structures from elastomeric materials.

Experimental researches were carried out by means of modern measuring complex INSTRON / E 3000, methods of integral calculation were used for processing of measurement results. Numerical modeling of the convective heat conduction problem was performed on the basis of the finite element method (FEM) with the use of modern software complexes.

Experiment Methodology. For solving this problem, experimental tests of samples of rubber-composite on prolonged cyclic deformation were conducted. The geometry of the samples meets the standards for mechanical tests of materials of this type (ISO 527-2-1B).

The samples had the following geometric parameters: actual thickness – 4.8±0.1 mm; width – 20 mm; length of the working part – 60 mm; total length – 150 mm. The thickness of the samples has variations within one percent due to the technological tolerances that exist in the production of composite sheets. Other parameters have exact values, since all samples were obtained by cutting using a steel shape with a standard size and a hydraulic press. Figure 1 shows a schematic drawing of the geometry of the samples (Fig. 1, *a*) and his photograph (Fig. 1, *b*). The samples were cut in the direction of reinforcement.



a *b*

Fig. 1. Geometry of samples for testing

Several series of experiments with cyclic loading of samples were conducted. Determination of the deformation curve was carried out using the specialized measuring instrument Instron.

It should be noted that for these materials, as a rule, the effect of Malin [7] is observed. At the same time, it should be emphasized that this effect is not studied in this study, and all properties are determined for materials in the stabilized state. In order to reduce this effect, 50 cycles of deformation with fixed amplitude of deformations of 10 % were preliminarily conducted at a deformation rate of 10 % / min.

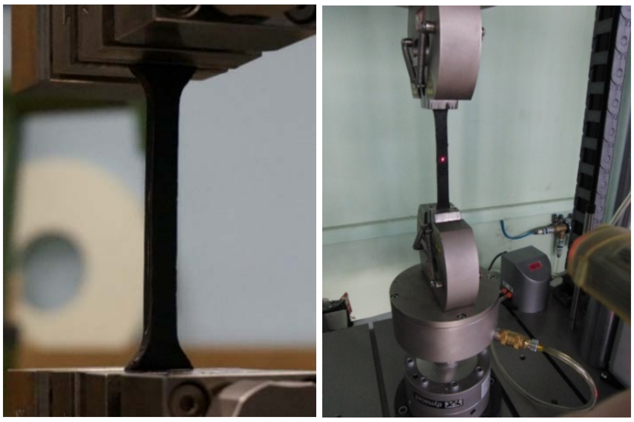


Fig. 2. Fixation of samples in an experimental installation

The bulk of the load consists of three stages. In the first stage, the sample was subjected to loading with a deformation size of 8 % at a deformation rate of 10 % / min.

At the second stage, the sample was subjected to cyclic deformation with a fixed value of amplitude and frequency. The values of the amplitudes of deformations are in the range 2...6 % with a 2 % step. Frequencies are in the range of 5 to 12.5 Hz in increments of 2.5 Hz.

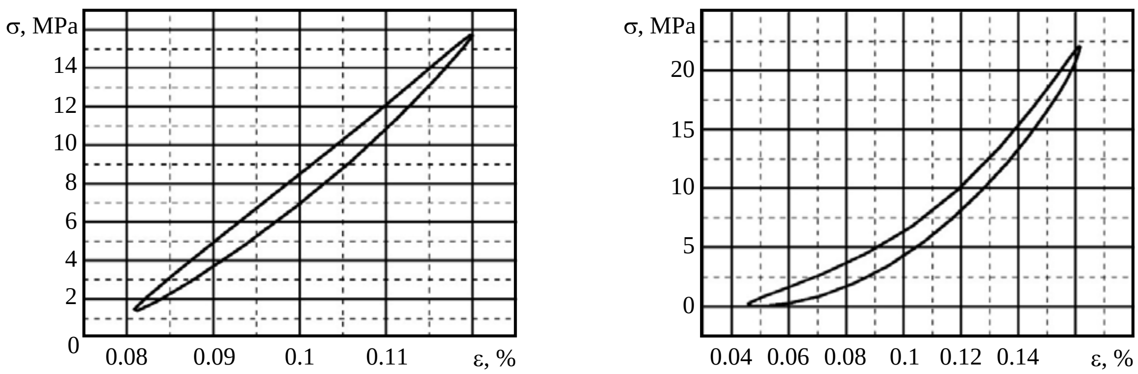
At the third stage, the sample was unloaded to a deformation value of – 8%.

The results are automatically recorded for each test in real time every 0.1 seconds. They are represented as the value of deformation and stress at each step of measurement, as well as the magnitude of energy emitted during the cycle.

In the course of experiments, the temperature was also taken at the center point of the surface of the sample with a periodicity of 0.5 min. The measurements were carried out using a laser thermometer mounted on a tripod (Fig. 2). The red dot on fig. 2 indicates the location of the temperature.

Results of experimental studies. The tests allowed evaluate the viscoelastic properties of the rubber composite in the direction of reinforcement in the stabilized state.

There the characteristic deformation curves obtained in these tests are presented in Fig. 3. The results show almost linear behavior of the composite at deformation with an amplitude of 2 % (Fig. 3, *a*). However, from the graphs in Fig. 3, *b* it can be seen that with the growth of the amplitude and frequency of the behavior of the material becomes substantially nonlinear.



a *b*

Fig. 3. Deformation curves of an elastomeric composite material sample in the direction of amplification: at an amplitude of 2 % and a frequency of 5 Hz (a); At an amplitude of 6 % and a frequency of 15 Hz (in the stabilized state) (b)

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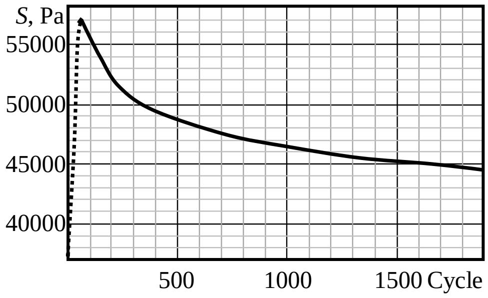
In the course of tests with cyclic nature of the load in the direction of cord amplification with a 2 % deformation amplitude and a frequency of 5 Hz, as well as with an amplitude of 6 % with a frequency of 15 Hz, the curve of dependence of the hysteresis loop area on the number of load cycles for a sample of an elastomeric composite material (Fig. 4).



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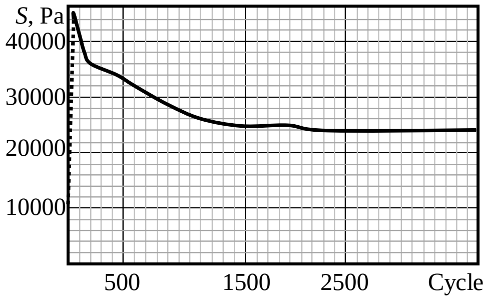


b

Fig. 4. Curve of dependence of hysteresis losses on the number of cycles: amplitude 2 % with a frequency of 5 Hz (a); Amplitude of 6 % with a frequency of 15 Hz (b)

Numerical simulation of the experiment. The results obtained during experiments with cyclic loading allow numerically simulate the experiment based on the finite element method (FE). There is the FE model of sample at Fig. 5. The thermal properties of the material are given in the table.

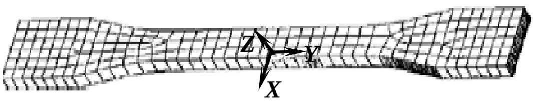
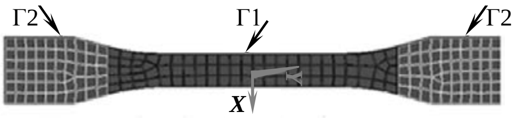


Fig. 5 FE model of sample

Thermal properties of the material

Coefficient of heat capacity, J/kg·K	Coefficient of thermal conductivity, W/m·K	Density, kg/m^3
1050	0.346	980

Boundary conditions were applied to the sample under the terms of its fixation. Conditions on convective heat transfer were imposed on the surface of the sample and the temperature of the environment was indicated (Fig. 6). The surface marked as Γ2 corresponds to the contact point of the sample with the metal clips. Here the coefficient of convective heat transfer is 88000.



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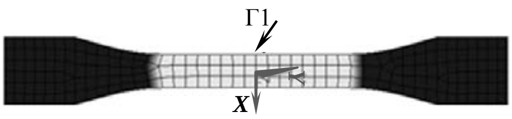

b

Fig. 6. Boundary conditions applied to the sample: conditions of convective heat transfer (a); heat generation rate (b)

The area Γ1 is the working part of the sample. The coefficient of convective heat transfer here is given in the form of a temperature function, the graph of which is given in Fig. 7.

The value of the heat generation rate is calculated from the area of the hysteresis loop, the size of which, in turn, has a functional dependence on time, as shown above (Fig. 4).

The function of the rate of heat generation is given as the boundary condition on the working surface of the sample with the mark Γ2 (Fig. 6, *b*) and has the following form:

$$\dot{Q}(t) = S(t)\,f\,, \qquad (1)$$

where f – Load frequency (Hz;

$S(t)$ – Hysteresis loop area.

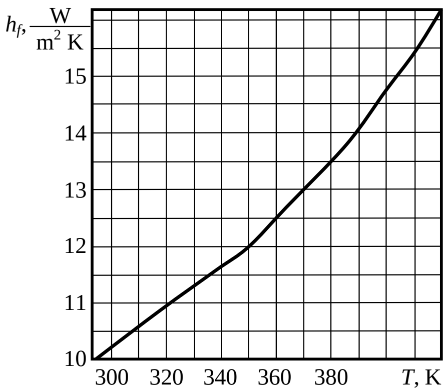

Fig. 7. Graph of the dependence of the coefficient of convective heat transfer on temperature

The area of the loop of hysteresis will be calculated using the following expression

$$S(t)=\begin{cases} S_{\max}\sin\left(\frac{\pi t}{2t_0}\right)\frac{1}{2}(1+\cos(2\pi ft)), & t\ge t_0;\\ ((S_{\max}-S_0)e^{-\lambda(t-t_0)}+S_0)\frac{1}{2}(1+\cos(2\pi ft)), & t<t_0, \end{cases} \quad (2)$$

where $S_{\max}$, S_0 – The value of the hysteresis loop area is maximal and in the stabilized state, respectively;

λ –Parameter of exponent, which determines the rate of stabilization of hysteresis loop area;

t_0 – time; which corresponds to the maximum value of the loop area.

Results of numerical simulation. During the numerical modeling of the experiment, the temperature distribution was obtained as a result (Fig. 8). The maximum temperature values can be observed in the working area of the sample.

Fig. 8 illustrates the temperature value at a load frequency of 5 Hz and with a deformation value of 2%. These values correspond to the stabilized state.

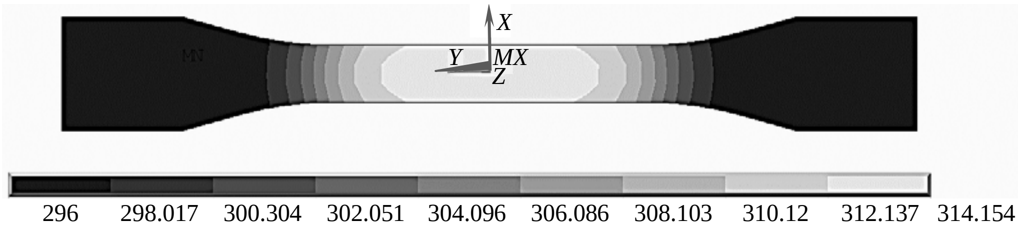

Fig. 8. Temperature distribution of the sample in the stabilized state

The nature of the heating process to the state of temperature stabilization for various load variations was also determined.

Fig. 9 shows the heating curve of the sample for the same load conditions as in Fig. 8. It was also noted that the initial stage is intensive heating. In more detail, it can be seen that the heating curve has a stepwise character with a rise in each load cycle. In the stabilized state, the heating curve is harmonic with an amplitude of 0.1 K.

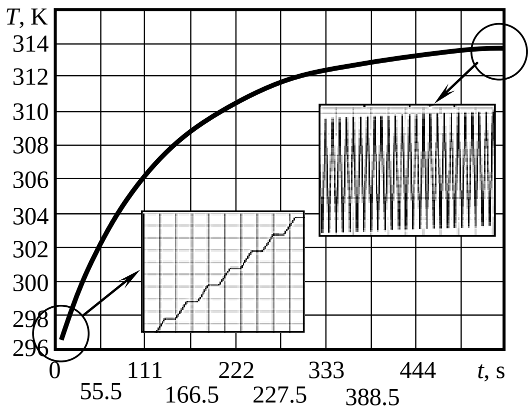

Fig. 9. Heating curve obtained as a result of calculation

Fig. 10 shows the heating curves obtained during the experiment and as a result of numerical simulation with loading amplitude of 2% and different frequencies. Comparison of the results of calculations with the data of physical measurements showed that the deviation is not more than 10 %.

In addition, graphs of temperature dependence (maximum observable temperature value and average temperature of the established process from the amplitude of deformations and loading frequency for the results of numerical and experimental studies (Fig. 11) were obtained.

Conclusions. In the course of this work, experimental studies were conducted to study the processes of self-heating of a gum-shaped composite reinforced by a textile cord. The samples were subjected to a cyclic load with a fixed amplitude of deformation and frequency. As a result of the experiment, the area of hysteresis loops was determined, the dependence of their value on the load time, as well as on the magnitude of deformations and load frequency, was established.

It was found that with increasing frequency the hysteresis losses decrease, and with increasing amplitude of deformations they grow. The obtained results were used to carry out numerical reproduc-

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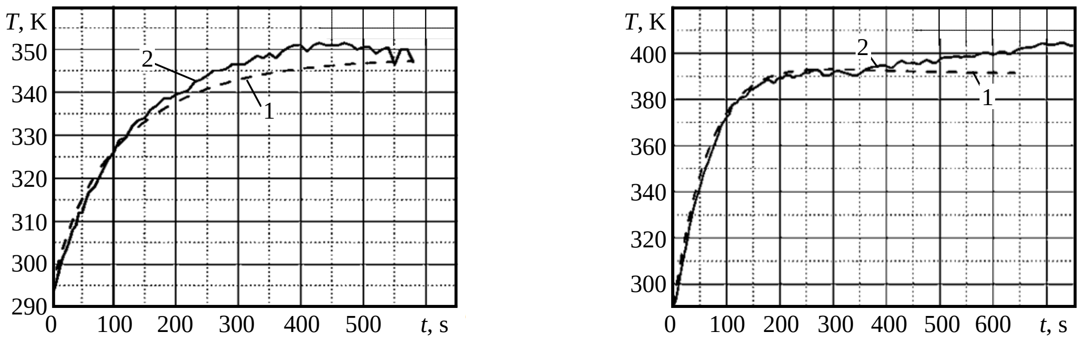
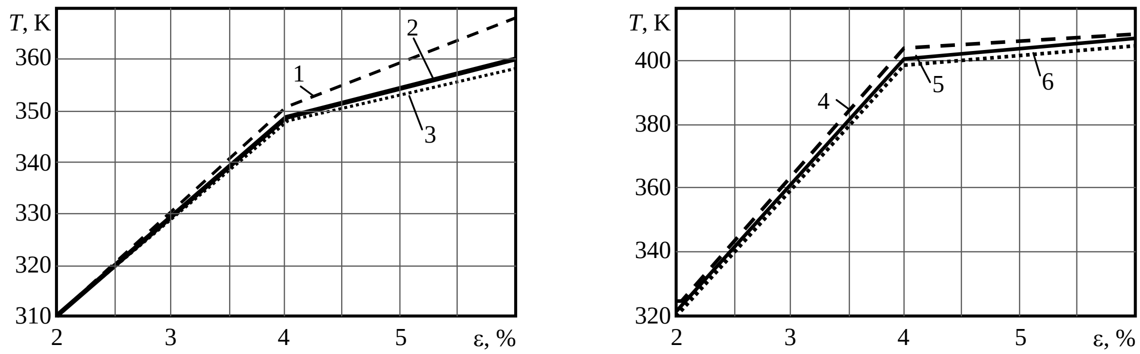
tion of this experiment in order to test the proposed algorithm for studying the processes of self-heating of rubber cords. In this case, the load is quasigarmonic, while taking into account the dependence of the amount of hysteresis losses on the load time that was set at the experimental stage. Also, during experiments, the temperature was measured on the surface of the sample.



a *b*

Fig. 10. Comparison of the results of the calculation and the experiment:
load frequency 5 Hz (a); load frequency 12.5 Hz (b): 1 – Calculation; 2 – Experiment



a *b*

Fig. 11. Comparison of the results of the experiment and numerical calculation:
1 – 5 Hz (Maximum value); 2 – 5 Hz (Calculation); 3 – 5 Hz (Average value); 4 – 12.5 Hz (Maximum value);
5 – 12.5 Hz (Calculation); 6 – 12.5 Hz (Average value)

As a result of the numerical solution of the problem of convective heat conduction, we obtained a pattern of temperature distribution by the model. Also received heating curves, the features of heating at the beginning of the load and in the stabilized state are set; the character of temperature dependence on frequency and amplitude of deformations is found.

Comparison of the results obtained during the experiment and numerical simulation shows good convergence of the parameters, the deviation is less than 10 %, which gives grounds to use the proposed method for the study of more complex structures from this material.

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