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Mathematical Model of Rheological Processes of Composite Materials Deformation

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***Abstract* —Inelastic materials, in particular, composites are widely used in industry. This necessitates the development and research of mathematical models to describe the rheological properties of such materials at different temperatures and types of loads. The principle of heredity for the study of composite materials leads to the construction of the most general equations that take into account hereditary effects, the influence of speed, types of loading, operating conditions, etc. such prominent relations are integral equations of the Voltaire type. According to the law of inheritance and the principle of superposition, the total deformation of a body consists of the instantaneous deformation, which is determined by the stress acting at a given moment in time and related to it by Hooke's law, and the inherited deformation. The heredity principle is the most general principle that can be the basis of studies of the rheological properties of inelastic materials. The article formulates and describes a mathematical model based on this principle, which describes the behavior of composite materials in different loads and temperatures modes. The purpose of the article is to develop an adequate model of the environment, quite simple and convenient for describing the rheological properties of composites under conditions of various loads and elevated temperatures. Objectives of the article: to present the developed model for describing the rheological properties of composite anisotropic materials; show the method of determining viscosity and temperature parameters for inelastic materials; to demonstrate the possibility of predicting the behavior of composites in different modes of loads and temperatures. The mathematical model is an integral equation with a creep nucleus. The nucleus of the model is chosen in the form of the Abel nucleus. The parameters of the Abel nucleus are determined by experiments on samples of anisotropic composites. The loading mode can be any, for example, stretching the sample at different load speeds, or stress relaxation at constant deformations. As determined, temperature heredity is not significant. The behavior of the material is determined only by the value of temperature at a given time. The temperature effect function can be selected as a normal degree dependence. The model is determined by three parameters. The parameter determination problem can be solved analytically, for simple load cases. More complex load cases, require the use of computer technology and methods of approximate calculations. The advantage of the proposed model is the possibility to transfer certain parameters from one load mode to another. The basic relations are given; the method of determining the parameters of the hereditary model is described; theoretical and experimental research is presented; the possibility of predicting the behavior of composite materials at different temperatures is shown.**

Keywords—model, heredity, temperature, deformation, composite materials, heredity nucleus, parameters

I. Introduction

Inelastic materials, in particular composites, are widely used in industry. This necessitates the development and study of mathematical models to describe the rheological properties of such materials at different temperatures and types of loads [1–3]. Viscosity and creep are inherent in composites and are especially felt at elevated temperatures. This leads to a close relationship between the fields of stress, strain, temperature. There are various models for describing the inelastic behavior of materials: from simple deformation theory, which does not take into account the dependence on load velocity to rather complex integrated models that take into account the hereditary nature of deformation and describe reversible and irreversible deformations. Differential models of the environment are convenient but do not describe the real performance of materials satisfactorily. Such models give only a qualitative description of the deformation process [4–8]. Parameters defined for one load type cannot be transferred to another. More common are integrated models that take into account hereditary effects, i.e. the "memory" of the material, as well as the influence of speed and type of load. The inability to transfer model parameters from one type of load to another is a disadvantage of many models [9]. Therefore, the issue of development and application of the model with parameters that can be determined from experiments with different types of loads and be able to predict the behavior of anisotropic composite at different temperatures is topical [10–15].

II. Goals and Objectives Of the Article

The article aims to develop an adequate model of the environment, quite simple and convenient for describing the rheological properties of composites under different loads and elevated Objectives of the article: to present the developed model for the description of rheological properties of composite anisotropic materials; to show the method of determining the viscosity and temperature parameters for inelastic materials; to demonstrate the ability to predict the behavior of composites in different modes of loads and temperatures [16–23].

III. Main Part

The most general principle that can be the basis of research on the rheological properties of inelastic materials is the principle of heredity. The article formulates and describes a mathematical model based on the specified

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principle that describes the behavior of composite materials in various load and temperature regimes.

The mathematical model is an integral equation with a creep core. The kernel of the model is chosen in the form of an Abel kernel. The parameters of the Abel kernel are determined using experiments on samples of anisotropic composites. The loading mode can be any, for example, stretching the sample at different load speeds, or stress relaxation at constant deformations.

The principle of heredity for the study of composite materials leads to the construction of the most general equations that take into account hereditary effects, the effect of speed, types of loading, operating conditions, and so on. Such notable relations are Volterian-type integral equations.

According to heredity law and the principle of superposition, complete deformation of the body consists of instantaneous deformation, which is determined by the stress acting at a given time and associated with Hooke's law, and hereditary deformation [24].

If at the moment in time τ the stress σ was applied, which proceeded for the $d\tau$ time, the material memorizes the action of this stress in the form of some small deformation $d\varepsilon$. The $d\varepsilon$ value is proportional to the stress value $\sigma(\tau)$, its time $d\tau$ and depends on the time, which passed from the ту τ moment till the current moment *t*, meaning $t-\tau$. To account for this dependence, it can be assumed that $d\varepsilon$ is proportional to some function in the following way:

$$d\varepsilon = \frac{1}{E} G(t-\tau)\sigma(\tau)\,d\tau \qquad (1)$$

Integrating by τ from 0 to *t*, adding instantaneous elastic deformation, we get:

$$\varepsilon = \frac{1}{E}\left(\sigma + \int_0^t G(t-\tau)\,\sigma(\tau)\,d\tau\right) \qquad (2)$$

Equation (2) is a linear equation of hereditary type [25–30].

The main problem in linear hereditary resilience is the choice of hereditary nuclei, which must meet two basic requirements, which are to correctly describe the behavior of the material and be such that the mathematical formulation and solution of problems are simple enough.

The Abel nucleus is the most simple of all possible integrating nuclei:

$$\frac{k}{(t-\tau)^{\alpha}}, \quad 0<\alpha<1 \qquad (3)$$

It describes the processes of deformation of various materials quite well, both metals, polymers, and composites. Its simplicity significantly expands the possibility of applying the model of hereditary type in calculations.

However, the application of linear theory to describe the processes of deformation of various materials is quite limited. Linear theory gives satisfactory results at moderate stresses, and for some materials the linearity region cannot be determined at all [31–39].

One way to construct a nonlinear defining relation is to generalize a linear equation. Rabotnov's equation is well known in this respect:

$$\varphi(\varepsilon) = \sigma + \int_0^t G(t-\tau)\,\sigma(\tau)\,d\tau \qquad (4)$$

This paper proposes and investigates a modification of equation (4), which turned out to be more convenient for the problems under consideration:

$$\psi(\sigma) = \varepsilon - \int_0^t K(t-\tau)\,\varepsilon(\tau)\,d\tau \qquad (5)$$

The advantage of this model is the transfer of all nonlinearity in the left part of the equation, in the so-called instantaneous deformation curve. Any deformation process that occurs over time is a "slip" from the instantaneous curve.

In model (5) we use the Abel nucleus:

$$\psi(\sigma) = \varepsilon(t) - \int_0^t \frac{k}{(t-\tau)^{\alpha}}\varepsilon(\tau)\,d\tau, \quad 0<\alpha<1 \qquad (6)$$

The question of the effect of temperature on mechanical properties for inelastic materials, in particular composite materials, the behavior of which largely depends on the time and speed of loading, is also very important. A temperature-based model has already been proposed for composite materials, which is based on the idea that the instantaneous deformation curve is independent of temperature.

This assumption leads to the idea that an increase in temperature at one load speed causes a "slip" from the instantaneous curve down, where the curve $\varphi(\varepsilon) = \sigma$ or $\psi(\sigma) = \varepsilon$ corresponds to the process of deformation of the material at absolute zero temperature. No matter what speed the material is loaded at 0^0K, its deformation diagram will correspond to the instantaneous one. The same diagram can be obtained at any other temperature if the deformation process occurs at an infinitely high speed [45–51].

For the accepted modification of the hereditary environment model taking into account the temperature let's record as follows:

$$\psi(\sigma) = \varepsilon(t) - \int_0^t K(t-\tau)\,\varepsilon(\tau) f_{\psi}(T(t),T(\tau))\,d\tau \qquad (7)$$

where $K(t-\tau) = \frac{k}{(t-\tau)^{\alpha}}$, $0<\alpha<1$ – abel nucleus; f_{ψ} – the function of temperature impact, which has to depend both on the temperature *t* at a given time, and on the history of its change τ.

The verification of the model preceding (7) had the form:

$$\varphi(\varepsilon) = \sigma(t) + \int_0^t G(t-\tau)\,\sigma(\tau) f_{\varphi}(T(t),T(\tau))\,d\tau \qquad (8)$$

Testing the model (8) on many composite materials revealed that the temperature inheritance is insignificant. The behavior of the material is determined only by the value of temperature at a given time, and the function of temperature can be chosen as the usual degree dependence of T^{γ}.

Therefore, we can assume that the model (7) of the study of the composite material, in particular, the rubber cord of the tires for which the experiments were performed, the function of temperature can also be selected as T ^ γ:

$$\psi(\sigma) = \varepsilon(t) - \int_0^t K(t-\tau)\,\varepsilon(\tau) T^{\gamma}(t)\,d\tau \qquad (9)$$

Thus, to fully describe the behavior of the composite material at different modes of load and temperature, it is necessary to determine three parameters $\propto$, k, γ. As it will be shown below, the parameters determined under one load mode and the constructed deformation curve can be used to predict the perfomance of the material under other types of loads and other conditions [40-44].

Let's consider the matter of determining the parameters of the hereditary model in the case of a nonlinear integral equation with the Abel nucleus.

In the case of processing experiments with load $\varepsilon = const$ або $\dot{\varepsilon} = const$ integral equation (5) becomes an ordinary algebraic relation.

Let's also consider the mode $\dot{\varepsilon} = const$. Then (5) will transform to:

$$\psi(\sigma) = \varepsilon - \int_0^t \frac{k}{(t-\tau)^\alpha} \dot{\varepsilon}\, \tau d\tau, \quad (10)$$

or, after transformation:

$$\psi(\sigma) = \varepsilon(1 - \frac{k}{(1-\alpha)(2-\alpha)} t^{1-\alpha}) \quad (11)$$

It follows from the concept of determining the instantaneous deformation curve that for the same σ for two deformation diagrams $\sigma - \varepsilon$, $\psi(\sigma)$ must be the same. Based on this, we have the following for the two deformation diagrams obtained at different speeds:

$$\varepsilon_1(1 - \frac{k}{(1-\alpha)(2-\alpha)} t_1^{1-\alpha}) = \varepsilon_2(1 - \frac{k}{(1-\alpha)(2-\alpha)} t_2^{1-\alpha}) \quad (12)$$

Choosing any other curves $\sigma - \varepsilon$, or any other two levels of ε_1, ε_2, which correspond to the same level σ, we obtain the second equation to determine the parameters of the nucleus of heredity. You can repeat the procedure several times and take the arithmetic mean of the values obtained as parameters. Further refinement of the parameters is due to the fact that the instantaneous deformation diagrams must match each other [52-56].

The instantaneous deformation curve is constructed by formula (11) for the known parameters $\propto$, k.

The entire studied time interval is divided into the required number of intervals $t_1, t_2 \dots t_n$. For each t_i using (11) respective $\psi(\sigma_i)$ is determined. Obtained graph $\psi(\sigma_i) - \sigma$ is the instantaneous deformation curve we were looking for. Similar calculations can be performed for each of the deformation curves at different velocities $\dot{\varepsilon}$. All obtained curves must coincide with each other, i.e. lie on the same chart. If this does not happen, the model parameters need to be refined.

A similar procedure for determining the parameters of the hereditary nucleus can be applied to other load modes, for example, stress relaxation, for which the integral in (6) is determined easily. According to certain parameters, it is possible to calculate deformation diagrams at other load modes taking into account (6).

Let's consider stress relaxation: $\varepsilon = const$. Then we have the equation:

$$\psi(\sigma) = \varepsilon(1 - \frac{k}{(1-\alpha)} t^{1-\alpha}) \quad (13)$$

Divide the time period into intervals. Each interval t_i corresponds to the value of $\psi(\sigma)$. From the curve $\psi(\sigma)$, calculated using the velocity deformation curves, remove the value of σ_i. Thus, the correspondence $t_i - \sigma_i$ is a stress relaxation curve calculated using the instantaneous strain curve and the parameters determined at high-speed load.

The advantage of the proposed model, which takes into account temperature in the hereditary type equation, compared to the temperature-time analogy, which is most often used in linear viscosity, is the assumption of the independence of the instantaneous strain diagram from temperature.

Therefore, the constructed $\psi(\sigma)$ can be used for calculations at other temperatures. It is only required to define the γ parameter and temperature function under integral sign in (9), which is presented as a degree function. Considering the experiments take place at room temperature $T = 20^0C = 293^0K$, it may be considered that:

$$\frac{k}{(1-\alpha)} = \frac{293^\gamma \eta}{(1-\alpha)}, \quad (14)$$

where η does not depend on the temperature.

Let's choose any two deformation curves that are obtained at different temperatures and any t_*value convenient for calculation, the same for both curves. In this case:

$$\psi(\sigma_1) = \varepsilon_1(1 - \frac{k}{(1-\alpha)(2-\alpha)} T_1^\gamma t_*^{1-\alpha});$$

$$\psi(\sigma_2) = \varepsilon_2(1 - \frac{k}{(1-\alpha)(2-\alpha)} T_2^\gamma t_*^{1-\alpha}) \quad (15)$$

Putting it in the following view:

$$\frac{\psi(\sigma_1) - \varepsilon_1}{\psi(\sigma_2) - \varepsilon_2} = \frac{\varepsilon_1}{\varepsilon_2} (\frac{T_1}{T_2})^\gamma . \quad (16)$$

Using logarithm we will receive parameter γ. Determining η from (14), which does not depend on the temperature. To clarify the parameter, the calculation can be repeated several times and the average taken.

The hereditary properties of the composite largely depend on the structural features determined by the manufacturing technology.

Testing of the described model was performed on samples of composite cut in different directions to take into account the anisotropy of the material. To determine the parameters and type of relationship between stresses and strains, a series of tests were conducted for uniaxial tensile at speeds $V_1 = 5\ mm/min$ and $V_2 = 200\ mm/min$.

The parameters of the experimental deformation curves of the samples cut in direction 1 were found using the method: $k = 0.023$, $\alpha = 0.9$. These parameters were used for calculating deformation diagrams of the samples cut in direction 2. Instantaneous deformation curves were constructed in both cases $\Psi(\sigma)$. It has been experimentally proven that it is not necessary to determine the set of heredity nuclei associated with anisotropy to analyze the complex stress state of the studied materials. One nucleus is enough, the parameters of which are determined from tests on samples cut in any direction.

The only difference is the instantaneous deformation curves, the knowledge of which corresponds to the knowledge of the matrix of elastic modules of anisotropic material for a linear hereditary medium. Therefore, we can assume that the parameters of the hereditary nucleus do not depend on the direction of cutting samples. Temperature parameter $\gamma = 0{,}55$ was established using the tests deformation diagrams at T=20° i T=120°C. It was used to forecast the material performance at $T = 70\ ^{\circ}C$

The result of the experiment is demonstrated in Fig. 1 and Fig. 2.

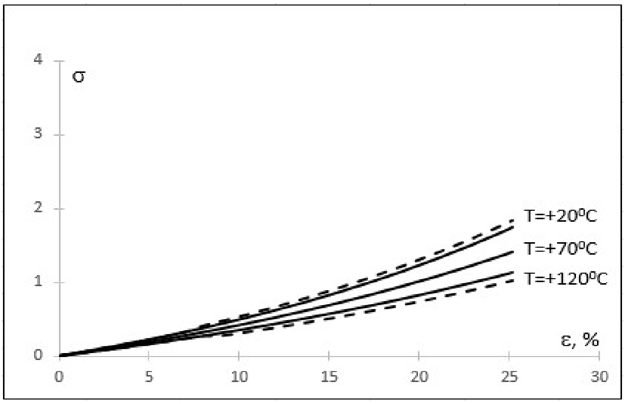

Fig. 1. Deformation diagram of the composite cut in direction 1:
V=200 mm/min, σ (H/mm^2), solid line – experiment,
dotted line – calculation.

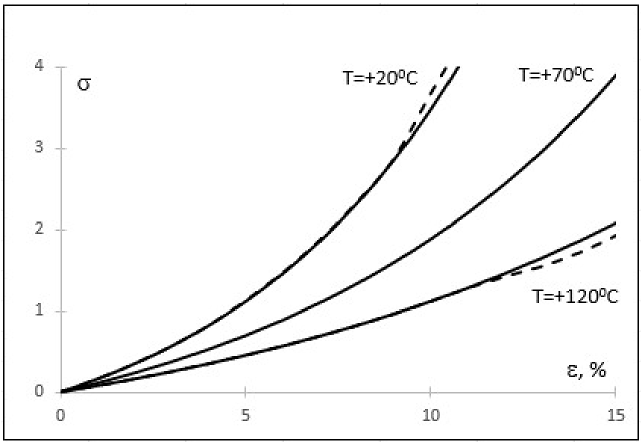

Fig. 2. Deformation diagram of the composite cut in direction 2:
V=200 mm/min, σ(H/mm^2), суцільна лінія – experiment,
dotted line – calculation.

As can be seen from the results of the calculations shown in Pic. 1 and Pic. 2, the error is small and is within the allowable 5–10%.

As determined, temperature heredity is not significant. The behavior of the material is determined only by the value of the temperature at a given time. The function of temperature influence can be chosen in the form of an ordinary power dependence. The model is defined by three parameters. For simple cases of loads, the problem of parameter determination can be reduced to an analytical solution. For more complex cases of loads, it is necessary to use computer equipment and methods of approximate calculations. The advantage of the proposed model is the possibility of transferring the specified parameters from one load mode to another. The main ratios are given; the method of determining the parameters of the hereditary model is described; theoretical and experimental studies are presented; the possibility of predicting the behavior of composite materials at different temperatures is shown.

IV. Conclusion

The most general principle that can be the basis of research on the rheological properties of inelastic materials is the principle of heredity. The article formulates and describes a mathematical model based on the specified principle, which describes the behavior of composite materials in different modes of loads and temperatures. The mathematical model is an integral equation with a creep core. The kernel of the model is chosen in the form of an Abel kernel. The parameters of the Abel kernel are determined using experiments on samples of anisotropic composites. The loading mode can be any, for example, stretching of the sample at different load speeds, or stress relaxation at constant deformations. As determined, temperature heredity is not significant. The behavior of the material is determined only by the value of the temperature at a given time. The function of temperature influence can be chosen in the form of an ordinary power dependence. The model is defined by three parameters. For simple cases of loads, the problem of parameter determination can be reduced to an analytical solution. For more complex cases of loads, it is necessary to use computer equipment and methods of approximate calculations. The advantage of the proposed model is the possibility of transferring the specified parameters from one load mode to another. The main ratios are given; the method of determining the parameters of the hereditary model is described; theoretical and experimental studies are presented; the possibility of predicting the behavior of composite materials at different temperatures is shown.

Inelastic materials, in particular, composites are widely used in industry. This necessitates the development and research of mathematical models to describe the rheological properties of such materials at different temperatures and types of loads. The principle of heredity for the study of composite materials leads to the construction of the most general equations that take into account hereditary effects, the influence of speed, types of loading, operating conditions, etc. such prominent relations are integral equations of the Voltaire type. According to the law of inheritance and the principle of superposition, the total deformation of a body consists of the instantaneous deformation, which is determined by the stress acting at a given moment in time and related to it by Hooke's law, and the inherited deformation.

The hereditary type model presented in the article allows taking into account the rheological properties of composite materials. The parameters of the model can be calculated using experimental curves obtained for any type of load. A convenient technology allows you to determine the parameters of the model and use them for anisotropic composites to predict the behavior at different temperatures.

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