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METHODS OF ASSESSING THE TECHNOLOGICAL SAFETY OF COMPLEX TECHNICAL AGRICULTURAL SYSTEMS

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Abstract. *The paper considers a method for estimating the service life of viscoelastic elements and takes into account such effects as aging, which affect the mechanism of structural failure. The presented method for assessing the technological safety of technical systems is suitable for assessing the durability of elements in which aging is very important and does not involve a violation of the geometric shape.*

Key words: *viscoelastic materials, cyclic loading, failure mechanism.*

Introduction

It is well known that an elastomer, as a solid deformable body, represents a multi-level self-organizing system in which the micro-, meso-, and macrolevels are organically interconnected. Experimental studies, including those employing fractal analysis, have demonstrated that the primary carriers of material structural change over time—i.e., the aging effect—are three-dimensional structural elements (commonly referred to in the literature as mesovolumes). The nature of such structural elements depends on the material's origin, its internal structure, loading conditions, and environmental influences. Studies of materials [1,2,3,4,5,6,7,8] indicate that the destruction patterns of these volumes at both the meso- and microlevels follow the law of similarity. This suggests that it is unnecessary to examine the microlevel mechanics of failure when assessing the mechanical characteristics of elastomers.

In this context, the model of aging (degradation) of elastomeric elements can be represented as follows:

a) An elastomeric element may be considered as a set of numerous "volumes";

b) Fatigue failure can lead to the formation of macrocracks, resulting in the destruction of one or several local volumes;

c) The propagation of "main" cracks is driven by the merging of macrocracks and is characterized by changes in the material's internal structure.

Research results

Given that thermal aging of rubber and aging under prolonged cyclic loading differ in nature, they will be considered separately.

Model of Thermal Aging

During thermal aging of rubber (in the absence of an aggressive external environment), physical and mechanical properties of the material change, regardless of whether it is in a deformed or undeformed state. These changes are caused by the simultaneous processes of structuring and degradation occurring within the rubber. Structuring involves the formation of a new molecular network, which leads to increased hardness, higher elastic modulus, and the emergence of residual deformations. Degradation, in contrast, involves the breakdown of the molecular network due to the rupture of main chains and cross-links, resulting in a reduction of the elastic modulus.

For the rubber materials under consideration, the structuring process prevails, leading to an increase in the elastic modulus and a decrease - up to the onset of failure - in the energy dissipation coefficient. The latter factor is of particular importance for predicting the durability of rubber elements, as the energy dissipation coefficient characterizes the material's ability to absorb energy. This leads to changes in the material's structure (without visible deformation of the specimen), which are manifested as significant changes in material parameters and, consequently, the actual loss of functional performance. For example, in the case of machine vibration isolators, the failure criterion may be defined as the attainment of a specific elastic modulus value, set based on the reliable operation requirements of a mechanical system—such as a vibration machine, vibration absorption system, etc.

Aging Model under Long-Term Cyclic Loading

In mechanics, the aging model under long-term cyclic loading is commonly referred to as the fatigue failure model. Under prolonged cyclic loading - accompanied by dissipative heating and the accumulation of microdamages within the volume and on the surface of the rubber matrix - it becomes practically impossible to isolate the material property contributions from the overall degradation process. Therefore, to denote this complex process, we will use both terms - aging and degradation/failure - understanding them as changes in the physical and mechanical properties of the material.

The key principles of this model are as follows: in its initial state, a viscoelastic system contains a certain level of microdamage, the concentration of which continuously increases under fatigue loading until it reaches a critical threshold, after which the system fails. The failure process is characterized by locality and discreteness. Microdamages are capable of dissipating energy, which reduces the stress intensity at the crack tip and may delay crack propagation. At the crack tip, local heating can reach the temperature of thermodegradation of the material.

Based on these concepts, the fatigue failure model of rubber can be presented as follows. During prolonged cyclic loading, the concentration of submicrocracks in the system increases until a state is reached where they begin to coalesce and locally form microcracks, whose size in rubber is typically on the order of 10–100 micrometers [5]. Phenomenologically, this is manifested as a continuous increase in shear modulus and a decrease in the energy dissipation coefficient. The mechanical characteristics of rubber change both due to the accumulation of microdamages and as a result of the general aging of the material. At this stage, aging effects are clearly predominant.

Further cyclic loading leads to the growth of microcracks, their local merging, and the initiation of main (macro) cracks. This moment may be considered as the point of local failure of the system. Subsequently, one or two main cracks begin to grow rapidly, ultimately leading the system to total failure.

At this stage of system degradation, a drastic change in macroscopic characteristics is observed: the shear modulus decreases, while the energy dissipation coefficient increases. Aging effects no longer play a major role; instead, the change in micro-level properties is primarily governed by the degree of material damage. Notably, the macrocracks themselves do not significantly influence these changes: they arise due to the cumulative microdamage throughout the material. As a rule, only integral (average) characteristics of the system are determined experimentally, while local variations in the material may be somewhat greater.

The mechanism of microcrack growth can be described as follows. A zone of elevated stress concentration forms at the crack tip. The temperature in this microvolume rises sharply, altering the rubber's structure in the surrounding region - potentially up to the point of thermodegradation. This results in the formation of thermomechanical failure zones. In regions located farther from the crack tip, microdefects appear; as their concentration increases and they merge, the crack undergoes a sudden (jump-like) growth.

A similar pattern is observed during the propagation of macrocracks in actual rubber structures. A macrocrack, depending on the applied stress field and design characteristics, propagates with a broad front. At the microscopic level, this front splits into multiple cracks, which may grow independently during certain stages and later merge. Each of these cracks is associated with the formation of a local microvolume of weakened material, allowing the cracks to propagate independently. At a certain point in this process, merging of local microvolumes at crack tips can occur, resulting in the discrete advancement of the macrocrack front. This is typically followed by a temporary arrest of the crack front, renewed growth of individual microcracks, their coalescence, and another sudden advance of the macrocrack. This model helps to explain the appearance of fractographic features such as ridges, striations, cleavage steps, and thermomechanical failure zones. The latter may also be associated with thermal instability in local microvolumes of the material. As temperature increases, the dissipation coefficient of rubber rises sharply. This can lead to further temperature elevation in the microvolume, thereby increasing both the dissipation coefficient and the self-heating rate—up to the point of material thermodegradation.

Mathematical Model of Rubber Aging

A deformable sample can be considered a thermodynamic system. The state of such a system is characterized by its internal energy. Based on this, we assume that there exists a correspondence between the degree of material degradation and its internal energy. Relying on this assumption, we can formulate a failure criterion.

The First Law of Thermodynamics, in the case where the sample is subjected to both mechanical deformation and non-mechanical forces (e.g., radiation), is expressed as:

$$\dot{U} = \sigma_{ij}\dot{\varepsilon}_{ij} + \dot{\chi}. \quad (1)$$

In this formula:

$\dot{U}$ – denotes the internal energy of the system;

χ – represents the energy of non-mechanical influence (in what follows, the dot notation indicates a time derivative).

As a result of these external influences, the internal energy of the system increases. However, every physical system tends to reach a state of minimal energy. Consequently, the accumulated internal energy is redistributed and consumed within the system. According to the First Law of Thermodynamics, the work performed internally within the system is directed toward altering its internal structure and releasing heat, that is:

$$\sigma_{ij}\dot{\varepsilon}_{ij} + \dot{\chi} = \dot{U}_p + \dot{q}, \quad (2)$$

In this formula:

U_p – is the portion of internal energy utilized for the restructuring of the system's internal structure, i.e., for damage and degradation;

$\dot{q}$ – is the portion of internal energy released as heat.

Over the time interval from t = 0 to t =t* the energy balance can be expressed as follows:

$$\int_0^{t^*} \sigma_{ij}\dot{\varepsilon}_{ij}dt + \int_0^{t^*} \dot{\chi}dt = \int_0^{t^*} \dot{U}_p dt + \int_0^{t^*} q dt.$$

$$\int_0^{t^*} \dot{U}_p dt = \int_0^{t*} \sigma_{ij}\dot{\varepsilon}_{ij}dt + \int_0^{t^*} \dot{\chi}dt - \int_0^{t^*} \dot{q}dt,$$

$$\int_0^{t^*} \dot{U}_p dt = \int_0^{t^*} \left(\sigma_{ij}\dot{\varepsilon}_{ij} + \dot{\chi} - \dot{q}\right)dt. \quad (3)$$

If we denote $\int_0^{t^*} \dot{U}_p dt$ as ΔU_p^* and assume that ΔU_p^* – is a material constant, then the system will fail at time t^*; from equation (3) the value of ΔU_p^*, can be determined t^*. Therefore, equation (3) serves as a creep (long-term strength) criterion and allows the prediction of the failure time of a characteristic volume of a solid under known deformation conditions and an experimentally determined material constant ΔU_p^*.

Thus, the presented models of thermal aging and aging under prolonged cyclic loading accurately represent the material degradation process. They explain the emergence of fractographic features (cleavage, grooves, fibrillar structures, ridges, fatigue crack retardation effects, and zones of localized thermomechanical failure) and most comprehensively reveal the interaction mechanism between energy dissipation and material aging. Based on the mathematical model of elastomer aging (degradation) with consideration of energy dissipation effects, the failure criterion for viscoelastic systems can be formulated as follows: the system will fail when the accumulated degradation energy ΔU_p reaches a certain critical value ΔU_p^*, which is a material constant.

Prediction of the Service Life of Rubber Components Under Long-Term Cyclic Loading with Consideration of Material Aging

The prediction of the service life of rubber components will be carried out based on the failure criterion described by equation (3).

$$\int_0^{t^*} \dot{U}_p dt = \int_0^{t^*} \sigma_{ij}\dot{\varepsilon}_{ij} dt + \int_0^{t^*} \dot{\chi} dt - \int_0^{t^*} \dot{q} dt. \quad (4)$$

To determine the stress fields at ν = const (ν – Poisson's ratio) and in the absence of mass forces (elastic formulation), quasi-static Lame equations are used

$$\Delta\vec{U} + \frac{1}{1-2\nu}\,\mathrm{grad}\,\mathrm{div}\,\vec{U} = 0, \quad (5)$$

In this formula:

$\vec{U}$ – is the displacement vector.

If we use some relations, we can arrive at the following form

$$\int_0^{t^*} \sigma_{ij}\dot{\gamma}_{ij} dt = \frac{G_0 a_0^2 \psi N^*}{4} f_1(x, y). \quad (6)$$

Let us make a number of assumptions that significantly simplify the solution to the problem, namely: the stress field is uniform, the heat flow is uniform and stationary.

Using these assumptions and neglecting the change in rheological characteristics during one deformation cycle, for the central point of the specimen:

$$\int_0^{t^*} \sigma_{ij}\dot{\gamma}_{ij} dt = \frac{G_0(N)\gamma_0^2}{2} \sum_{N=1}^{N^*} \psi(N), \quad (7)$$

In this formula:

$$N^* = \frac{\omega}{2\pi} t^*;$$

$\psi(N)$ – dissipation coefficient, a function of the number of deformation cycles.

Summary and conclusions

The proposed algorithm was applied to predict the service life of various types of rubber components. It is also suitable for forecasting the durability of different structural elements in which material aging plays a dominant role and where failure does not involve a change in the geometric shape of the product.

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