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A refined method for determining rheological parameters of the maxwell-gurevich equation from polymer relaxation curves using the example of epoxy resin edt-10

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Abstract. This paper presents a refined methodology for determining the rheological parameters of the nonlinear generalized Maxwell-Gurevich equation, which is widely used to describe creep and relaxation processes in polymer materials. Despite the extensive application of this constitutive model in polymer mechanics, existing methods for identifying its key parameters – namely the high-elasticity modulus E_∞, the rate modulus m_{cr}, and the initial relaxation viscosity $\eta_{cr,0}$ – often yield approximate values that do not fully capture the material's behavior across different deformation levels. The proposed approach addresses this limitation through a comprehensive two-stage algorithm based on the processing of stress relaxation curves at various initial strain levels. In the first stage, preliminary parameter values are obtained using an analytical approximation method that involves polynomial fitting of creep strain data and logarithmic transformation of the relaxation viscosity coefficient. The second stage employs numerical optimization techniques implemented in the Python programming language, specifically the scipy.optimize.fmin function for global minimum search, combined with the fourth-order Runge–Kutta method for solving the differential equation of creep strain rate. The methodology was validated using experimental data for EDT-10 epoxy resin – a thermosetting polymer widely employed in structural applications – tested at 20°C under six different initial relative deformations ranging from 0.008 to 0.035. The relaxation curves were digitized from classical literature sources and processed according to the developed algorithm. The results demonstrate that the rheological parameters of the Maxwell-Gurevich equation exhibit significant dependence on the initial strain (stress) level, contrary to the common assumption of their constancy for a given temperature. Specifically, the high-elasticity modulus E_∞ decreases nonlinearly from 19142.71 MPa to 2643.07 MPa as the initial deformation increases, while the rate modulus mcr shows an increasing trend from 3.58 MPa to 22.48 MPa. The initial relaxation viscosity $\eta_{cr,0}$ decreases by approximately two orders of magnitude, from $8.14 \cdot 10^5$ MPa·h to $1.33 \cdot 10^4$ MPa·h. Functional relationships approximating these dependencies as functions of the initial elastic strain were established with high correlation coefficients (R^2 ranging from 0.9776 to 0.9988 for individual curves). A comparative analysis was conducted with three previously published parameter sets for EDT-10 epoxy resin. The comparison reveals that traditional constant-parameter approaches significantly underestimate the high-elasticity modulus and lead to excessively rapid stress relaxation, particularly at higher initial strain levels (>0.0155), where the solution degenerates. In contrast, the proposed strain-dependent

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parameterization yields theoretical relaxation curves that closely match the experimental data across the entire range of deformations, with coefficients of determination R^2 exceeding 0.97 for all curves except the lowest strain level (0.008), where digitization errors are more pronounced. The methodology demonstrates robustness and can be extended to other polymer materials and loading conditions, including creep tests where the stress remains constant. The findings have important implications for the mechanics of polymer structures, adhesive joints, and composite materials, where accurate prediction of long-term deformation behavior under various stress states is essential for reliable design and service life assessment. Future research directions include validation of the proposed hypothesis for creep curves and investigation of temperature-dependent parameter variations.

Keywords: Maxwell-Gurevich equation, rheological parameters, relaxation curves, epoxy resin EDT-10, nonlinear viscoelasticity, numerical optimization, polymer mechanics, creep, parameter identification, Python

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1. INTRODUCTION

In the mid-20th century, a nonlinear generalized Maxwell constitutive relation in the form proposed by G.I. Gurevich (hereinafter referred to as the constitutive relation or the Maxwell-Gurevich equation) was introduced in the Soviet Union. During numerous tests, it demonstrated a very good description of creep strain development in polymer materials. Moreover, it is valid for both linear and cross-linked polymers.

Since the Maxwell-Gurevich equation was mainly used in closed laboratories until the end of the 1980s, open sources contain a very few experimental results based on this constitutive relation. One of the key works on the experimental study of polymer creep curves and their relaxation curves is the work by V.F. Babich [1]. Subsequently, the Maxwell-Gurevich equation was considered in detail in the book by A.L. Rabinovich [2] for various variants of the stress-strain state of specimens.

The Maxwell-Gurevich equation is most often represented in differential form, expressing the rate of creep strain development:

$$\frac{\partial \varepsilon_{cr,ik}}{\partial t} = \left[\frac{3}{2}\left(\sigma_{ik} - p\delta_{ik}\right) - E_{\infty}\varepsilon_{cr,ik} \right] \frac{1}{\eta_{cr}}, \qquad \left(i,k = 1,2,3\right). \tag{1}$$

In equation (1), the creep strain rate is represented in the form of partial derivatives, since its coefficients on the right-hand side are generally functions of many factors: stress level, temperature, etc. In equation (1), nonlinearity also lies in the relaxation viscosity coefficient η_{cr}, which is equal to

$$\eta_{cr} = \eta_{cr,0} \cdot \exp\left\{ -\frac{1}{m_{cr}} \left[\gamma^{*} p + \left| \frac{3}{2}\left(\sigma_{rr} - p\right) - E_{\infty}\varepsilon_{cr,rr} \right|_{\max} \right] \right\}. \tag{2}$$

In equations (1) and (2), the following notations are used: E_{∞} is high-elasticity modulus; m_{cr} is rate modulus; $\eta_{cr,0}$ is initial relaxation viscosity coefficient; p is mean stress value $p = (\sigma_{xx}+\sigma_{yy}+\sigma_{zz})/3$; δ_{ik} is Kronecker symbol

$$\delta_{ik} = \begin{cases} 1 \text{ if } i = k; \\ 0 \text{ if } i \neq k. \end{cases}$$

Reference [2] indicates that the parameter γ^* from equation (2) is negligible and is omitted from direct calculations.

To solve problems of determining the stress-strain state in building structures made of polymer materials, it is necessary to have the values of two elastic parameters (elastic modulus E and Poisson's ratio ν) and three rheological parameters (high-elasticity modulus E_∞, rate modulus m_{cr}, and initial relaxation viscosity coefficient $\eta_{cr,0}$). The procedure for determining these parameters is very laborious [2].

In work [3], an alternative method was presented for determining the desired parameters of the Maxwell-Gurevich equation based on a single pass along the relaxation curves of polyvinylchloride for different temperature regimes. The value of the total relative strain was constant and amounted to $\varepsilon = 0.03$.

Subsequently, the method for determining the physical-mechanical parameters of the material was adjusted to work with polymer creep curves. In work [4], the Maxwell-Gurevich equation described concrete creep. The result of comparing the theoretical curves with ex-perimental data showed good agreement between them.

Work [5] presents a method for determining parameters using nonlinear optimization techniques by means of the MATLAB software package.

In work [6], the search for polymer relaxation curves is carried out using neural networks. For this purpose, an extensive database of polymer relaxation curves is initially created, and subsequent training is performed on various neural models.

Many scientific works present the study of creep and relaxation curves using epoxy resins as an example. In the present work, the thermosetting epoxy resin EDT-10 is considered. In the available works of Academician V.I. Andreev [7], Professor R.A. Turusov [8, 9], and Professor B.M. Yazyev [10], the physical-mechanical parameters for the Maxwell-Gurevich equation for EDT-10 and polymethylmethacrylate are given. In this case, the physical-mechanical parameters of polymers are functions of temperature and do not depend on the level of stress or strain in the material.

The problem of accurately determining the physical-mechanical parameters of polymers is very relevant, since it underlies many areas of mechanics: modeling of adhesive joints based on analytical and numerical-analytical methods [11-14], based on the finite element method [15], calculation of residual stresses in a cooling polymer cylinder upon exiting an extruder [16], description of nonlinear viscoelastic and thixotropic properties of human blood using a modified Maxwell-Gurevich-Rabinovich model [17], problems of buckling of polymer plates under nonlinear creep [18], calculation of wooden arches considering nonlinear creep [19], as well as other optimization problems for cylindrical structures made of polymer materials [20].

2. METHODS AND MATERIALS

The proposed algorithm for determining the physical-mechanical parameters of a polymer is based on processing the polymer's relaxation curves at various strain levels.

Hypothesis: The physical-mechanical parameters in the Maxwell-Gurevich equation are functions of the total strain at the initial moment of time ($t = 0$), at which only elastic strains develop in the polymer.

Consider a polymer specimen, schematically represented in Figure 1a, under a uniaxial stress state. The cross-sectional area of the specimen is A, the initial length is L_0. The rod is clamped in a testing machine and stretched with some force F, elongating by ΔL. The specimen is fixed in the extreme position, meaning its length does not change. The total relative strain of the rod after stretching is equal to

$$\varepsilon = \frac{\Delta L}{L} = \text{const} . \qquad (3)$$

Since the entire stress-strain state exists only in the axis system "x", the index "xx" will be omitted hereafter.

In expression (3), the total relative strain of the rod is equal to the sum of two components: the elastic component and the creep strain

$$\varepsilon = \varepsilon_{el,xx} + \varepsilon_{cr,xx} = \varepsilon_{el} + \varepsilon_{cr} = \text{const}\,. \tag{4}$$

Since the external force is equal only to the support reactions F arising in the grips, by performing an imaginary section I–I (Figure 1c), the internal force N will also be equal to $N = F$. Then a stress σ will arise in the specimen, equal to

$$\sigma = \sigma_{xx} = \frac{N}{A} = \frac{F}{A}\,.$$

Here the index "xx" was omitted, since the entire stress-strain state exists only in the axis system "x".

When studying experimental curves, the entire time interval is approximated by a non-uniform grid. When studying theoretical data, the entire time interval is approximated by a uniform grid

$$\omega_t = \left\{ t_j = (j-1)h_t, \quad h_t = \frac{t_{\max}}{N_t - 1}; \quad j = 1,2,...,N_t \right\},$$

where h_t is uniform grid time step; $t_{\max}$ is maximum time in the studied data; N_t is index of the last node of the time grid, both in the case of uniform and non-uniform grids (in both cases, the first node of the time grid has index 0).

Since the creep process develops over a relatively long period of time, acceleration in strain development can be neglected and each node of the time grid can be considered as operating in a static formulation. That is, the problem is solved in a quasi-static formulation.

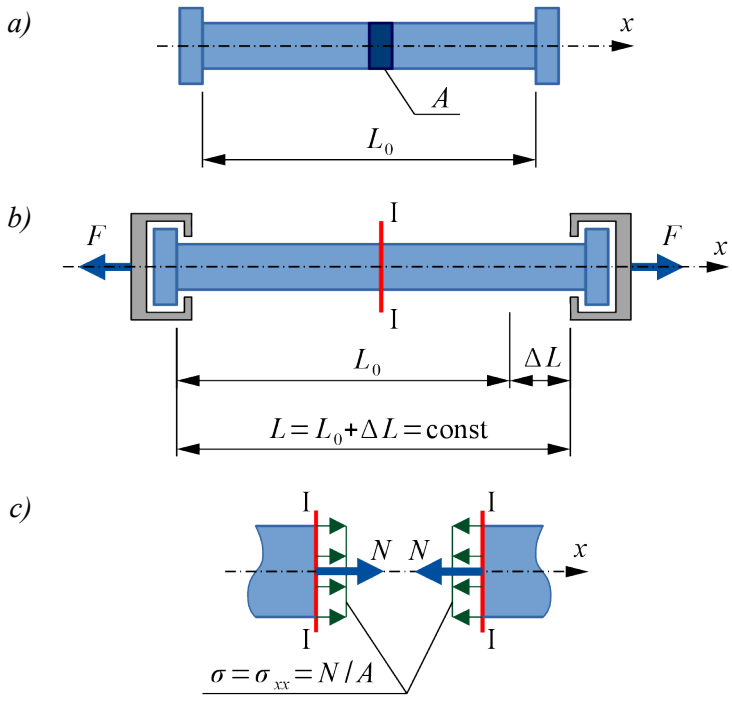

Fig. 1. Testing setup for a polymer specimen under stress relaxation.

Consider the Maxwell-Gurevich equation (1) for the case of uniaxial tension.

In this case, the physical-mechanical parameters at each moment in time for a specific loading will be constant, therefore equation (1) can be written in total derivatives:

$$\frac{d\varepsilon_{cr}}{dt} = \frac{f_{cr}}{\eta_{cr}}, \tag{5}$$

where $f_{cr} = \sigma - E_{\infty}\varepsilon_{cr}$ is the stress function.

To determine the refined values of the physical-mechanical parameters of the Maxwell-Gurevich equation, several stages are used. At the first stage, the method of preliminary determination of the desired parameters is applied [3, 21]. In this case, the values obtained are very rough. At the second stage, optimization functions are used, implemented using the Python programming language.

Let us consider the first stage in detail. At the initial moment of time, creep strains are absent. Consequently, the total strain (4) is represented only by the elastic component. Then, the elastic modulus of the material can be found

$$E = \frac{\sigma_0}{\left(\varepsilon = \varepsilon_{el,0}\right)}. \tag{6}$$

In expression (6), the lower indices show the number of the node in the time grid, i.e., $\sigma_0 = \sigma\left(t_0 = 0\right)$ and so on.

It is assumed that at the final moment of time, the rate of creep strain development (5) tends to zero, then it becomes possible to determine an approximate value of the high-elasticity modulus

$$\frac{d\varepsilon_{cr,Nt}}{dt} = \frac{f_{cr,Nt}}{\eta_{cr}} \approx 0, \tag{7}$$

and, since the relaxation viscosity coefficient η_{cr} cannot be equal to an infinitely large number, the stress function f_{cr} in expression (7) must be equal to zero

$$f_{cr,Nt} = \sigma_{Nt} - E_{\infty}\varepsilon_{cr,Nt} = 0 \quad \rightarrow \quad E_{\infty} = \frac{\sigma_{Nt}}{\varepsilon_{cr,Nt}},$$

where σ_{Nt} and $\varepsilon_{cr,Nt}$ are respectively, the stress and creep strain on the time grid at the node with index N_t, i.e., at the final moment of time.

To process experimental data on stress relaxation in a polymer, 3 parameters are passed: the value of the total relative strain $\varepsilon = \text{const}$, the time vector $t = [t_0, t_1, ..., t_j, ..., t_{Nt-1}, t_{Nt}]$, and the stress vector $\sigma = [\sigma_0, \sigma_1, ..., \sigma_j, ..., \sigma_{Nt-1}, \sigma_{Nt}]$. Now, having the value of the elastic modulus, at each time node it is possible to obtain the value of the creep strain $\varepsilon_{cr,j}$

$$\varepsilon = \varepsilon_{el,j} + \varepsilon_{cr,j} = \text{const} = \frac{\sigma_j}{E} + \varepsilon_{cr,j} \quad \rightarrow \quad \varepsilon_{cr,j} = \varepsilon - \frac{\sigma_j}{E}.$$

Having the vector of creep strains ε_{cr}, it is convenient to approx-imate them at each point using a polynomial

$$\varepsilon_{cr,j} = a \cdot t^2 + b \cdot t + c.$$

This can be readily done using the standard polyfit function, present in many programming languages.

This is done to determine the creep strain rate at each point

$$\frac{d\varepsilon_{cr,j}}{dt} = 2 \cdot a \cdot t + b = v_{cr,j}.$$

Then from expression (5), the initial relaxation viscosity coefficient at each moment of time will be equal to

$$\eta_{cr,j} = \frac{f_{cr,j}}{v_{cr,j}},$$

where $f_{cr,j} = \sigma_j - E_\infty \varepsilon_{cr,j}$.

For further transformations, the value of the relaxation viscosity (2) is considered and the value of its natural logarithm is found

$$\ln \eta_{cr} = \ln\left[\eta_{cr,0} \cdot \exp\left(-\frac{f_{cr}}{m_{cr}}\right)\right] = \ln \eta_{cr,0} - \frac{f_{cr}}{m_{cr}}. \quad (8)$$

A replacement is introduced

$$\xi = \ln \eta_{cr,0}; \quad \psi = -\frac{1}{m_{cr}}.$$

In this case, expression (8) can be represented as a first-degree polynomial

$$y = a \cdot x + b,$$

in which $y = \ln \eta_{cr}$; $x = f_{cr}$.

Reusing the polyfit function, the values of ξ and ψ are determined, then

$$\eta_{cr,0} = \exp \xi; \quad m_{cr} = -\frac{1}{\psi}.$$

Thus, at the first stage, all three parameters of the Maxwell-Gurevich equation describing the behavior of polymers under creep conditions become known: E_∞, m_{cr}, and $\eta_{cr,0}$.

Now let us consider the second stage in detail. It consists of the sequential selection of the desired parameters using the global minimum search function built into Python. The optimize.fmin() function from the scipy package is used. For this, all actions are performed according to the following algorithm: a total of 500 iterations were used. For each experimental point, according to the values of the parameters of the Maxwell-Gurevich equation obtained at the previous stage, a theoretical relaxation curve was constructed. The deviation of the obtained theoretical stress value from the theoretical curve was determined. The use of optimization functions was carried out to select such values of the desired parameters at which the square of the deviation of the stress values from the experimental data and the theoretical curve was minimal. At each stage, the obtained values of m_{cr} and $\eta_{cr,0}$ were set, and the optimal value of E_∞ was selected. Then, conversely, the value of E_∞ was set and the optimize.fmin() function was run to find the optimal values of m_{cr} and $\eta_{cr,0}$.

To reconstruct each curve, the Runge-Kutta method was used. For each experimental point, its time value was divided into 1000 intervals (the number of time nodes was $N_j = 1001$), for which the Runge–Kutta method was used, meaning the error at the final integration in-terval is of the order $O\left(h^4\right)$. The value of the creep strain served as the dependent variable to be integrated. For

convenience, in expression (7) we represent the creep strain growth rate ε_{cr} as a derivative with respect to time t:

$$\varepsilon'_{cr} = f\left(t, f_{cr}\right), \quad \varepsilon_{cr}\left(t_0\right) = \varepsilon_{cr,0}.$$

The value of the creep strain at the subsequent moment of time is determined by the iterative formula:

$$\varepsilon_{cr,j+1} = \varepsilon_{cr,j} + \frac{h_t}{6}\left(k_0 + k_1 + k_2 + k_3\right).$$

The determination of the coefficients proceeds in four stages:

$$k_0 = f\left(t_j, \varepsilon_{cr,j}\right);$$
$$k_1 = f\left(t_j + \frac{h_t}{2}, \varepsilon_{cr,j} + \frac{h}{2}k_0\right);$$
$$k_2 = f\left(t_j + \frac{h_t}{2}, \varepsilon_{cr,j} + \frac{h}{2}k_1\right);$$
$$k_3 = f\left(t_j + h_t, \varepsilon_{cr,j} + h_t k_2\right).$$

It is convenient to express the current stress through relative strains:

$$\sigma_j = E\varepsilon_{el,j} = E\left(\varepsilon - \varepsilon_{cr,j}\right).$$

As applied to the problem under consideration, the coefficients k_0–k_3 are written:

$$h_t = t_{j+1} - t_j;$$

$$f_{cr}^{\mathrm{I}} = E\cdot\left(\varepsilon - \varepsilon_{cr,j}\right) - E_\infty\varepsilon_{cr,j}; \quad \eta_{cr}^{\mathrm{I}} = \eta_{cr,0}\cdot\exp\left(-\frac{f_{cr}^{\mathrm{I}}}{m_{cr}}\right); \quad k_0 = \frac{f_{cr}^{\mathrm{I}}}{\eta_{cr}^{\mathrm{I}}};$$

$$f_{cr}^{\mathrm{II}} = E\cdot\left[\varepsilon - \left(\varepsilon_{cr,j} + \frac{h_t}{2}k_0\right)\right] - E_\infty\left(\varepsilon_{cr,j} + \frac{h_t}{2}k_0\right); \quad \eta_{cr}^{\mathrm{II}} = \eta_{cr,0}\cdot\exp\left(-\frac{f_{cr}^{\mathrm{II}}}{m_{cr}}\right); \quad k_1 = \frac{f_{cr}^{\mathrm{II}}}{\eta_{cr}^{\mathrm{II}}};$$

$$f_{cr}^{\mathrm{III}} = E\cdot\left[\varepsilon - \left(\varepsilon_{cr,j} + \frac{h_t}{2}k_1\right)\right] - E_\infty\left(\varepsilon_{cr,j} + \frac{h_t}{2}k_1\right); \quad \eta_{cr}^{\mathrm{III}} = \eta_{cr,0}\cdot\exp\left(-\frac{f_{cr}^{\mathrm{III}}}{m_{cr}}\right); \quad k_2 = \frac{f_{cr}^{\mathrm{III}}}{\eta_{cr}^{\mathrm{III}}};$$

$$f_{cr}^{\mathrm{IV}} = E\cdot\left[\varepsilon - \left(\varepsilon_{cr,j} + h_t k_2\right)\right] - E_\infty\left(\varepsilon_{cr,j} + h_t k_2\right); \quad \eta_{cr}^{\mathrm{IV}} = \eta_{cr,0}\cdot\exp\left(-\frac{f_{cr}^{\mathrm{IV}}}{m_{cr}}\right); \quad k_3 = \frac{f_{cr}^{\mathrm{IV}}}{\eta_{cr}^{\mathrm{IV}}}.$$

3. RESULTS AND DISCUSSION

The relaxation curves were scanned from work [2], digitized, and processed using the algorithm described above. The experimental data were obtained for a specimen tested at an ambient temperature of 20°C with relative strains of the specimen of 0.008, 0.012, 0.0155, 0.0195, 0.027, and 0.035.

Table 1. Results of processing relaxation curves of EDT-10 at a temperature of 20°C.

Line number	ε	σ_0, MPa	E, MPa	E_∞, MPa	m_{cr}, MPa	$\eta_{cr,0}$, MPa·h	R2
1	0.0080	24.132	3 016.50	19 142.71	3.5796	814 325.89	0.97759
2	0.0120	35.546	2 962.17	12 286.59	7.8821	171 095.93	0.99449
3	0.0155	46.114	2 975.09	9 086.47	9.5142	299 559.14	0.99650
4	0.0195	53.897	2 763.95	6 692.29	9.5414	79 279.56	0.99653
5	0.0270	60.795	2 251.67	3 770.80	9.7987	128 929.72	0.99777
6	0.0350	74.499	2 128.54	2 643.07	22.4780	13 280.21	0.99875

Based on the data, dependencies $f(\varepsilon(t=0)=\varepsilon_{el}(t=0))$, were constructed, which are presented in Fig. 2. Analysis of the data from Table 1 shows that line number 1 stands out in terms of convergence. This can be explained by the fact that in the case of small stresses, the difference between the stresses at each point of the experimental data is small. Consequently, the error increases during the scanning of the available graphs and their subsequent processing.

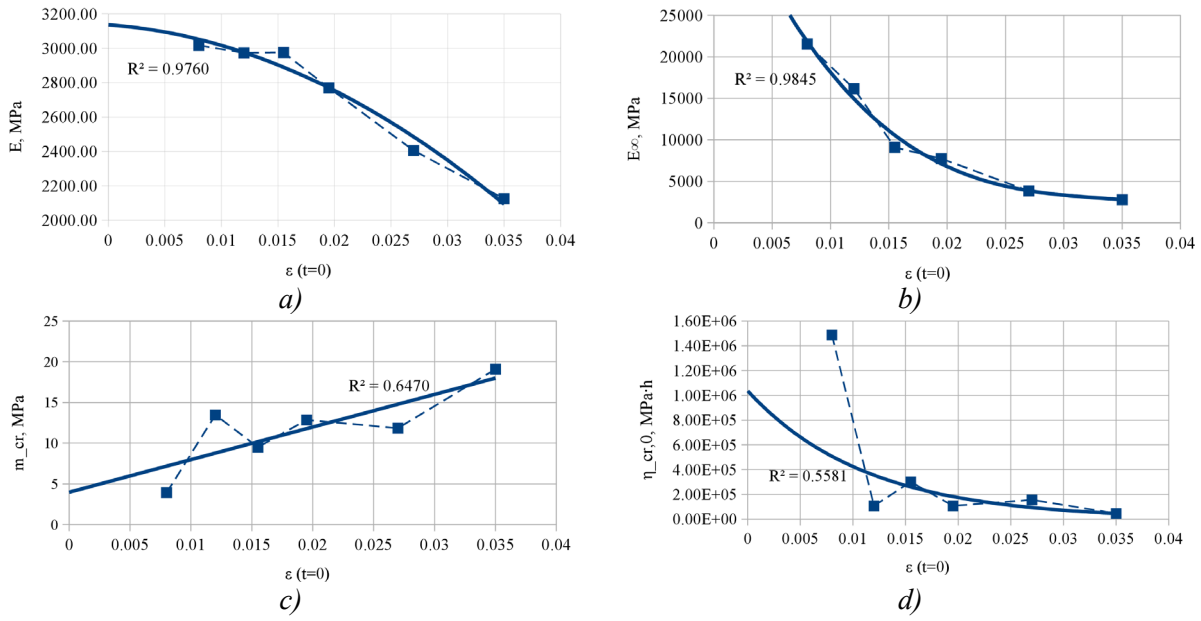

Fig. 2. Approximation of Maxwell-Gurevich parameters based on processing relaxation curves of EDT-10.

As a result, the following functional dependencies for the parameters of the Maxwell-Gurevich equation were obtained:

$$E\left(\varepsilon_{el,t=0}\right)=-712496.669352976\cdot\varepsilon_{el,t=0}^{2}-4868.95028807223\cdot\varepsilon_{el,t=0}+3136.1340273271;$$
$$E_\infty\left(\varepsilon_{el,t=0}\right)=-946064223.995305\cdot\varepsilon_{el,t=0}^{3}+96244894.7148046\cdot\varepsilon_{el,t=0}^{2}-$$
$$-3359857.36478379\cdot\varepsilon_{el,t=0}+43048.1935324347; \quad (9)$$
$$m_{cr}\left(\varepsilon_{el,t=0}\right)=401.087665289983\cdot\varepsilon_{el,t=0}+3.95718476972365;$$
$$\eta_{cr,0}\left(\varepsilon_{el,t=0}\right)=1036743.25033224\cdot\exp\left(-89.3286850314555\cdot\varepsilon_{el,t=0}\right).$$

As a result of comparing the theoretical curves constructed based on dependencies (9) with the original experimental data (Figure 3a), the following data reliability values were obtained for each line:

- Line 1, $\varepsilon_{el,0} = 0.0080$, $R^2 = 0.64363$: $E = 3051.58$ MPa; $E_\infty = 21\,844.62$ MPa; $m_{cr} = 7.17$ MPa; $\eta_{cr,0} = 5.0735 \cdot 10^5$ MPa·h;
- Line 2, $\varepsilon_{el,0} = 0.0120$, $R^2 = 0.97188$: $E = 2975.11$ MPa; $E_\infty = 14\,954.37$ MPa; $m_{cr} = 8.77$ MPa; $\eta_{cr,0} = 3.5492 \cdot 10^5$ MPa·h;
- Line 3, $\varepsilon_{el,0} = 0.0155$, $R^2 = 0.97129$: $E = 2889.49$ MPa; $E_\infty = 10\,570.22$ MPa; $m_{cr} = 10.17$ MPa; $\eta_{cr,0} = 2.5963 \cdot 10^5$ MPa·h;
- Line 4, $\varepsilon_{el,0} = 0.0195$, $R^2 = 0.99414$: $E = 2770.26$ MPa; $E_\infty = 7\,113.15$ MPa; $m_{cr} = 11.78$ MPa; $\eta_{cr,0} = 1.8162 \cdot 10^5$ MPa·h;
- Line 5, $\varepsilon_{el,0} = 0.0270$, $R^2 = 0.97807$: $E = 2485.26$ MPa; $E_\infty = 3\,873.19$ MPa; $m_{cr} = 14.79$ MPa; $\eta_{cr,0} = 9.2941 \cdot 10^4$ MPa·h;
- Line 6, $\varepsilon_{el,0} = 0.0350$, $R^2 = 0.99303$: $E = 2092.91$ MPa; $E_\infty = 2\,790.68$ MPa; $m_{cr} = 18.00$ MPa; $\eta_{cr,0} = 4.5483 \cdot 10^4$ MPa·h.

The worst convergence is observed with line 1. As mentioned earlier, this is due to the inaccura-cy of data processing when scanning graphs and their processing. When working with modern digital data, better convergence of the theoretical line with the experimental data should be expected.

To assess the reliability and the effect provided by the refined methodology, a comparison was made with existing data for EDT-10 parameters of the Maxwell-Gurevich equation.

According to the work of Professor Turusov [8]:

$$\begin{aligned} E(T_C) &= (-1.75 \cdot T_C + 352.5) \cdot 10 \text{, [МПа];} \\ E_\infty(T_C) &= (-3 \cdot T_C + 315) \cdot 10 \text{, [МПа];} \\ m_{cr}(T_C) &= (-0.0011 \cdot T_C + 0.475) \cdot 10 \text{, [МПа];} \\ \eta_{0,cr}(T_C) &= 10\,443 \cdot \exp(-0.0275 \cdot T_C) \cdot 10 \cdot 3\,600 \text{, [МПа·ч].} \end{aligned} \tag{10}$$

According to the works of Professor Turusov and Professor Yazyev [3, 4]:

$$\begin{aligned} E(T_C) &= 4\,000 \cdot \exp\left(-\exp\left(\frac{(T_C + 273.15) - 339}{36.7}\right)\right) \text{, [МПа];} \\ E_\infty(T_C) &= \frac{2.4 \cdot 10^6}{(T_C + 273.15)} - 6120 \text{, [МПа];} \\ m_{cr}(T_C) &= -0.0155 \cdot (T_C + 273.15) + 7.73 \text{, [МПа];} \\ \eta_{0,cr}(T_C) &= 36\,000 \cdot \exp\left(\frac{9\,500}{T_C + 273.15} - 21\right) \text{, [МПа·ч].} \end{aligned} \tag{11}$$

According to the work of Academician Andreev [7]:

$$\begin{aligned} E(T_C) &= 8\,302 - 17.5 \cdot (T_C + 273.15) \text{, [МПа];} \\ E_\infty(T_C) &= 11\,340 - 30 \cdot (T_C + 273.15) \text{, [МПа];} \\ m_{cr}(T_C) &= 7.75 - 0.011 \cdot (T_C + 273.15) \text{, [МПа];} \\ \eta_{0,cr}(T_C) &= 685 \cdot 10^8 \cdot \exp(-0.0275 \cdot (T_C + 273.15)) \text{, [МПа·ч].} \end{aligned} \tag{12}$$

The results of determining the parameters of the Maxwell-Gurevich equation using equations (10)–(12) at a temperature of 20°C are given in Table 2. The corresponding theoretical re-laxation curves, constructed using the parameters determined according to formula (10), are shown in Fig. 3b; according to formula (11) are shown in Fig. 3c; according to formula (12) are shown in Fig. 3d.

The results of comparing the theoretical curves obtained by formula (9) with the curves ob-tained by formulas (10)–(12) show that the refined formulas (9) provide very good agreement with the experimental data. In turn, formulas (10)-(12) give very underestimat-ed values of the high-elasticity modulus, which leads to the fact that when the initial rela-tive strain level exceeds 0.0155, the relaxation curves change very rapidly. At large values of initial strain, the solution degenerated.

Table 2. Parameters of the Maxwell-Gurevich equation for EDT-10 at a temperature of 20°C.

Parameter	Eq. (26)	Eq. (27)	Eq. (28)
E, MPa	3175.00	3002.95	3171.88
E_∞, MPa	2550.00	2066.94	2545.50
m_{cr}, MPa	4.53	3.19	4.53
$\eta_{cr.0}$, MPa·h	$2.1690 \cdot 10^8$	$3.2369 \cdot 10^9$	$2.1606 \cdot 10^7$

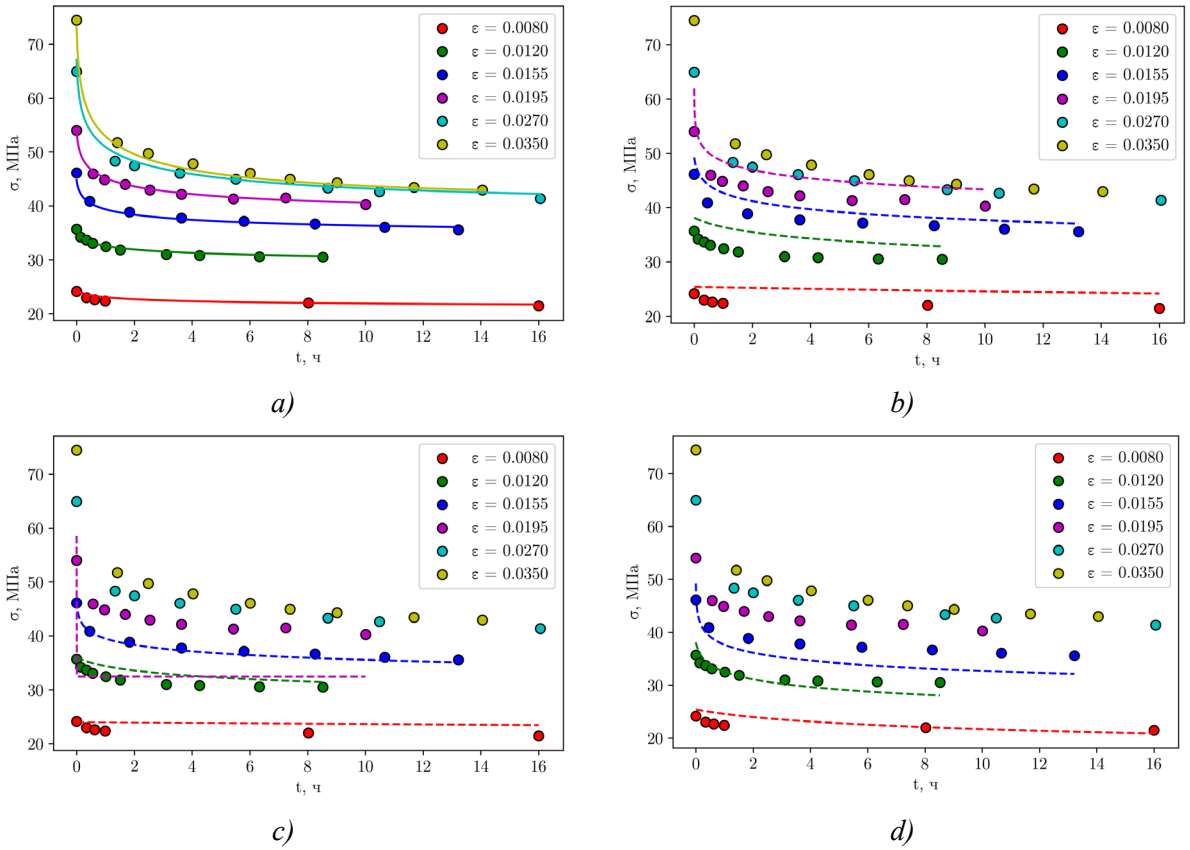

Fig. 3. Results of matching theoretical curves with the original experimental data: *a)* based on the proposed method for determining polymer parameters as functions of initial stress (strain); *b)* based on the parameters proposed in work [8]; *c)* based on the pa-rameters proposed in works [3, 4]; *d)* based on the parameters proposed in work [7].

4. CONCLUSIONS

For many years, to describe creep processes using the Maxwell-Gurevich equation, formulas for determining its parameters were used that provided values for a specific temperature and did not depend on the level of initial strain, or, in other words, the level of the stress state. The conducted studies for EDT-10 epoxy resin show that this approach is very limited and does not correspond to real relaxation curves.

At the same time, there is a great opportunity for expanding the research. For example, a hy-pothesis was used that the parameters of the Maxwell-Gurevich equation depend on the initial stress-

strain state. In this case, very good agreement of the constructed relaxation curves with the experimental data is observed. In the future, it is necessary to conduct sim-ilar studies for polymer creep curves, since in this case the stress is a constant value and, consequently, the elastic component of the total relative strain. It becomes possible to find the Maxwell-Gurevich parameters as functions of the elastic component of strain at each moment of time. If relaxation curves are constructed from these dependencies, it will be possible to verify the limits of applicability of the hypothesis used.

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