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CREEP OF POLYTETRAFLUOROETHYLENE UNDER VARIOUS LOADING CONDITIONS

L.I. OGORODOV, I.P. NICKOLAEVA, E.L. YAKOVLEVA, O.V. FOMINYKH

Peter the Great Saint-Petersburg Polytechnic University
29 Polytechnicheskaya St., St. Petersburg, 195251, Russia

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This article contains results of experimental research of polytetrafluoroethylene (PTFE) deformation and creep under linear and plane stresses. During the tests predetermined values of real stresses considering current deformation were constant. The equation of mechanical states considering instant elastic, viscoelastic, instant plastic and viscoplastic components of total deformation was obtained. The equation is used for the description of PTFE deformations (F-4, F-4D, F-4D0) under stationary and non-stationary cyclic loads in flat stress condition with an application of material constant volume condition, condition of similarity of deviators of stresses and deformations and with the input of parameters which are functions of the form of stress deviators. The results of PTFE creep investigation under real stresses reaching ultimate values are relevant and unique.

Keywords: creep, polytetraftorethylene, mechanical equation of states, static loadings, cyclic loadings, flat stress state, ultimate deformations

ПОЛЗУЧЕСТЬ ПОЛИТЕТРАФТОРЭТИЛЕНА ПРИ РАЗЛИЧНЫХ УСЛОВИЯХ НАГРУЖЕНИЯ

Л.И. ОГОРОДОВ, И.П. НИКОЛАЕВА, Е.Л. ЯКОВЛЕВА, О.В. ФОМИНЫХ

Санкт-Петербургский политехнический университет Петра Великого
ул. Политехническая, д. 29, Санкт-Петербург, Российская Федерация, 195251

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В статье представлены результаты экспериментальных исследований деформации и ползучести политетрафторэтилена (ПТФЭ) при линейных и плоских напряженных состояниях. Во время испытаний заданные значения истинных напряжений с учетом текущей деформации были постоянными. Получено уравнение механических состояний, учитывающее мгновенноупругие, вязкоупругие, мгновеннопластические и вязкопластические компоненты полной деформации. Уравнение используется для описания деформаций ПТФЭ (F-4, F-4D, F-4D0) при стационарных и нестационарных циклических нагрузках в условиях плоского напряженного состояния с применением условия постоянства объема материала, условия подобия девиаторов напряжений и деформаций и ввода параметров, которые являются функциями вида девиаторов напряжений. Результаты исследования ползучести ПТФЭ при реальных напряжениях, достигающих предельных значений, являются актуальными и уникальными.

Ключевые слова: ползучесть, политетрафторэтилен, механическое уравнение состояний, статические нагрузки, циклические нагрузки, плоское напряженное состояние, конечные деформации

Introduction. One of the directions of the development of engineer durability calculations of structural elements theory is consideration of their rheonomous properties in order to describe the processes of long-term deforming and destruction. From the one hand, for calculating creep and long-term durability of structural elements it is necessary to use the equation of mechanical states which describes complicated deformation processes. From the other hand, kinematic equation of damages should be used in deformation type. The materials show rheonomous and hereditary features in deformation processes as well as in long-term destruction. Despite of the fact that there are a lot of theoretical and experimental researches, the question of choosing adequate description method of deformational processes for different classes of polymer materials under non-stationary loading and complex stress cannot be finally solved, especially in the most complex thermomechanical loadings [1–7]. The requirements of practical applicability for the resulting mechanical state equation in some cases of cyclic loading makes us to make a compromise in accuracy while describing complex deformation processes. The task is to reduce this compromise to the logical minimum.

The development of cyclic creep model provides new opportunities for experimental research task formulation, makes experiment purposeful and allows to choose test program for checking the theory.

Research targets. Studies of creep of partially crystal polymer and composite materials on polymer base remain topical. The influence of complex static and cyclic stress state and non-stationary loading conditions on deformation process mostly remains unclear.

Research targets are:

1. According to the short-term monotonic loading tests data, to make up an equation of mechanical states in terms of real stresses and deformations under complex stress state for direct and reverse creep for three modifications of tetrafluoroethylene.

2. To research and to describe creep of the same materials under non-stationary static and cyclic stationary and non-stationary loading

3. To make a conclusion about the possibility of formularization of destruction deformation criteria for studied materials.

Materials and testing method with predetermined intensity of real stresses. The samples were made of pipe blanks of polytetrafluoroethylene F-4, F-4D by turning on the lathe tool and part of F-4D blanks were annealed; F-4D$_0$ blanks were heated until 80 °C with the following cooling in the heating stove. The degree of materials' crystallinity was detected by German – Weidinger's method and it is: 30% for F-4, 45% for F-4D, 38% for inner surface of F-4D$_0$, 25% for outer surface of F-4D$_0$. The densities of these materials are: for F-4 – 2.25 g/sm^2, for F-4D and for F-4D$_0$ – 2.23 g/sm^2.

The samples were thin-walled tubes with the wall thickness t_0 = 1.0 mm in working part and the length of working part l_p = 120 mm. The outer diameter (D$_0$) of F-4 and F-4D working parts is 23.5 mm, for F-4D$_0$ – 26 mm. The wall thickness fluctuations along the working part did not exceed 0.05 mm. The fluctuations of working parts lengths were within ± 1 mm and the fluctuations of outer diameter – within ± 0.1 mm. The samples were fixed in special sealing caps.

Sample tests were held on equipment [25; 26], which allow to study mechanical properties of materials under biaxial stress state with static and cyclic loading.

Lateral sample deformation was measured on the base l_0 = 50 mm by optical system with the value of division 0.01 mm. Transverse deformation was measured by arrow indicator. Temperature was 22 ± 1 °C.

The intensity of real stress values for tubular sample under flat stress state with static loading was obtained by formula:

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{(\overline{\sigma_x} - \overline{\sigma_\theta})^2 + \overline{\sigma_x}^2 + \overline{\sigma_\theta}^2}. \quad (1)$$

Under cyclic loading the intensity of maximum stress value per cycle was obtained by formula:

$$\sigma_i^{\max} = \frac{1}{\sqrt{2}}\sqrt{(\overline{\sigma_x}^{\max} - \overline{\sigma_\theta}^{\max})^2 + (\overline{\sigma_x}^{\max})^2 + (\overline{\sigma_\theta}^{\max})^2}. \quad (2)$$

Real stress components (axial $\overline{\sigma_x}$ and tangential $\overline{\sigma_\theta}$) were measured with considering current values of outer diameter (D) and thickness of the wall (t). The thickness of the wall was measured from the condition of constant value. The ratio between main stress components $n = \sigma_x/\sigma_\theta$ was established by choice of equipment plunger pair [25]. The delay time of equipment adjustment was not exceed 2 minutes, besides the fluctuations of stress intensity were not exceed 5% from set value of stress intensity σ_i or $\sigma_i^{\max}$ and fluctuations n were not exceed 6%.

Obtained experimental data under short time loading and creep with static loading are presented in the form of deformation curves in coordinates $\sigma_i - \varepsilon_i$ and creep curves in coordinates $\varepsilon_i^{\max} - \tau$. The intensity of real (logarithmic) stresses were obtained by formula:

$$\varepsilon_i = \frac{\sqrt{2}}{2}\sqrt{(\varepsilon_x - \varepsilon_\theta)^2 + (\varepsilon_\theta - \varepsilon_\tau)^2 + (\varepsilon_\tau - \varepsilon_x)^2}. \quad (3)$$

Real deformation components $\varepsilon_x, \varepsilon_\theta, \varepsilon_\tau$ were obtained by following dependences, considering current sample dimensions D, t and current base l (the sample length):

$$\varepsilon_x = \ln\frac{l}{l_0};\quad \varepsilon_\theta = \ln\frac{D-t}{D_0-t_0};\quad \varepsilon_\tau = \ln\frac{t}{t_0}. \quad (4)$$

Lode's parameter for stresses is calculating:

$$\mu_S = 2\frac{\sigma_2}{\sigma_1} - 1\mu_S = 2\frac{\sigma_2}{\sigma_1} - 1, \quad (5)$$

where σ_1 and σ_2 – the main stresses.

Tests results. ***Polytetrafluoroethylene deformation under short time loading.*** Short time loading PTFE deformation tests were held under linear and flat stress states with various ratios of axial and tangential stresses ($n = \sigma_x/\sigma_\theta$) in conditions of proportional loading. For PTFE there is an influence of stress state type on deformation curve, besides the material shows the highest rigidity when the ratio σ_x/σ_θ is close to equiaxial tension and the lowest – when it is under linear stress state. The variation of the loading speed from 0.03 MPa/sec. to 0.3 MPa/sec. influences on the deformation curves insignificantly.

The law of immediate deformation was studied by tests on the fast sample unloading from the fixed level of stress intensity under various types of stress state. Non-linear dependences of instantly elastic deformation from stress intensities for studied fluoroplastics are presented in an article [26]. According to the results of the measurements, the transverse deformation coefficient values under axial tension are vary from 0.3 to 0.48.

For the selection of the law of instant plastic deformation (the term is conditional) the data of the tests on the multiple loading with the speed $d\sigma_i/dt$ = 0.1–0.3 MPa/sec., with the registration of the σ_i and ε_i levels and further instant sample unloading was used. After exposure of at least one hour, permanent (instant elastic) deformations were measured. The dependence of instant plastic fluoroplastics deformations from the stress intensity is presented in the article [27]. Instant plastic deformations of fluoroplastics depend on the type of the stress state.

Direct and reverse creep under static loading. Direct creep is the increase of deformations in time under permanent real stresses (i.e. under constantly decreasing loads) (fig. 1–3). Complete deformation is the sum of four components: instant elastic, instant plastic, viscoplastic, viscoelastic [7–13]. To study viscoelastic creep deformation the tests on reverse creep (fig. 4–6) were held (returning after loading).

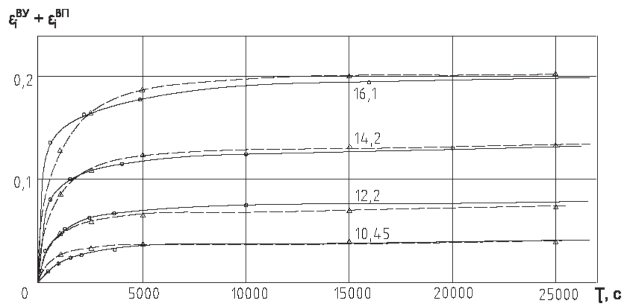

Fig. 1. Rheonomic F-4D$_0$ creep dependence (*n* = 0.5) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

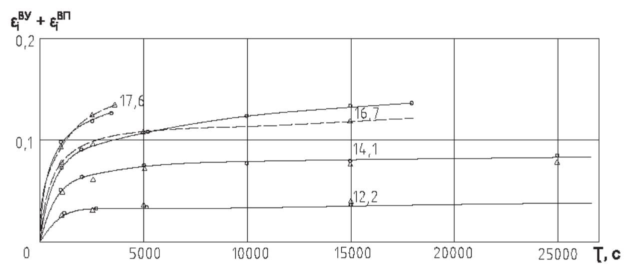

Fig. 2. Rheonomic F-4D$_0$ creep dependence (*n* = 1.15) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

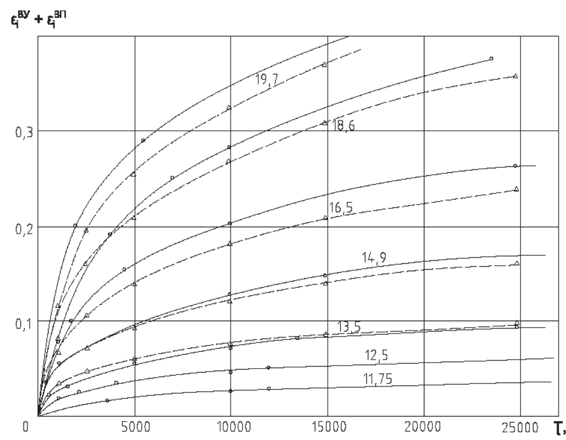

Fig. 3. Rheonomic F-4D creep dependence (*n* = 0.5) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

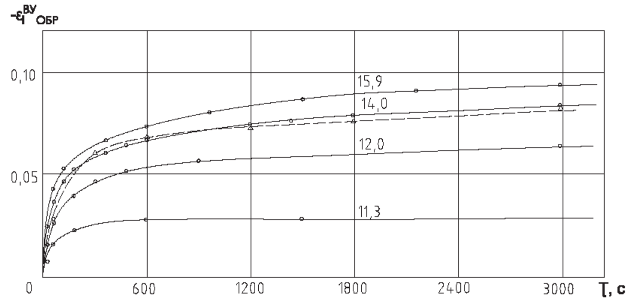

Fig. 4. Reverse F-4 creep curves (*n* = 0.5) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

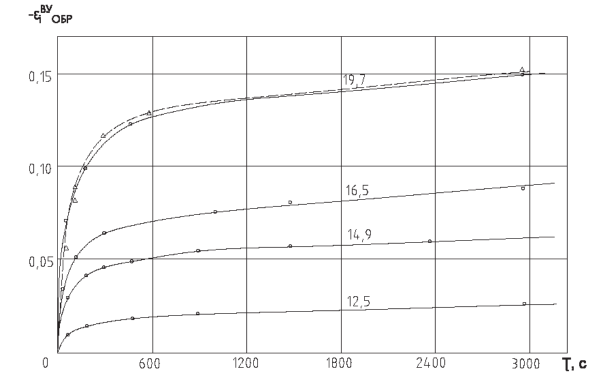

Fig. 5. Reverse F-4D creep curves (*n* = 0.5) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

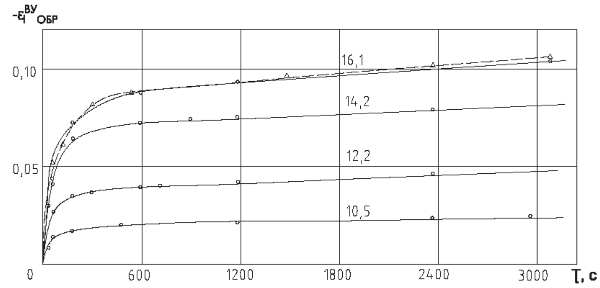

Fig. 6. Reverse F-4D$_0$ creep curves (*n* = 0.5) under various intensities of real stresses σ_i:
o – experimental curves; Δ – calculated curves

As a result, the complete equation of mechanical states in stress and deformation intensities (σ_i, ε_i) under stationary loading was obtained, besides the condition of deformation speeds and stress deviators similarity is observed [27]:

$$\varepsilon_i = \frac{2(1+\nu)\sigma_i}{3E_0\left(1-\frac{\sigma_i}{\sigma_{**}}\right)} + \gamma\left[(\alpha-\beta\mu_S)e^{m\left(\frac{\sigma_i}{\sigma_x}\right)}-1\right] + \int_0^{\tau}(a-b\mu_S)c\frac{\sigma_i}{\sigma_*}\left[A_1e^{-\frac{\tau}{\mu_1}}+A_2e^{-\frac{\tau}{\mu_2}}\right]d\theta + \int_0^{\tau}(d-l\mu_S)k\left(\frac{\sigma_i}{\sigma_*}-\delta\right)\left[A_3e^{-\frac{\tau}{æ}}\right]d\tau. \qquad (6)$$

Table 1

Constant equations of mechanical states

Parameters	Studied materials		
	F-4	F-4D	F-4D$_0$
E$_0$, MPa	800	900	615
σ_{**}, MPa	27.5	28.5	22.5
ν	0.48/0.50	0.48/0.50	0.48/0.50
ϒ	$1\cdot10^{-2}$	$1\cdot10^{-2}$	$1\cdot10^{-2}$
α	0.05	0.20	0.25
β	0.03	0.06	0.08
m	2.80	1.65	2.20
σ_*, MPa	10	10	10
a	1	1	1
b	0.1	0.1	0.6
c	0.30	0.08	0.26
n	3.2	3.7	2.8
A$_1$	$5.5\cdot10^{-2}$	$11\cdot10^{-4}$	$9.5\cdot10^{-4}$
A$_2$	$1.7\cdot10^{-2}$	$1.8\cdot10^{-4}$	$1.8\cdot10^{-4}$
μ_1, sec.	110	110	85
μ_2, sec.	2475	3200	3000
d	1	1	1
l	0.3	0.3	0.5
δ	1.05	1.18	1.17
k	3.95	1.89	4.00
A$_3$	$7\cdot10^{-6}$	$14\cdot10^{-6}$	$26\cdot10^{-6}$
æ, sec.	$14.0\cdot10^{-3}$	$14.1\cdot10^{-3}$	$1.5\cdot10^{-3}$

Non-stationary static loading modes of studying materials. Non-stationary static loading modes are presented on the fig. 7–10. Here also the dependences of real deformations from time are shown. According to the comparison of experimental and calculated data, generally, the calculation reproduces the creep process under complex loading mode with satisfactory accuracy. The experiment showed, that the differences are mostly connected with insufficient accuracy in approximation of functions $A_1e^{-\frac{\tau}{\mu_1}}+A_2e^{-\frac{\tau}{\mu_2}}$. To describe viscoelastic component of the complete deformation in this function, it is necessary to take more than two exponents. One of the additional exponents has to have the relaxation time in the following interval: $10\cdot10^3$ sec. ≤ μ ≤ $15\cdot10^3$ sec.

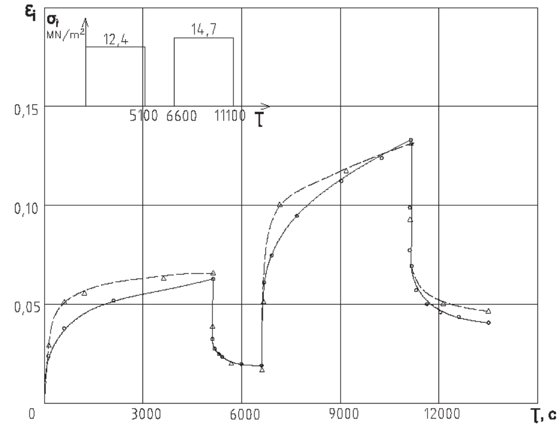

Fig. 7. Non-stationary static loading mode and creep curves F-4D (*n* = 0.5):
o – experimental curves; Δ – calculated curves

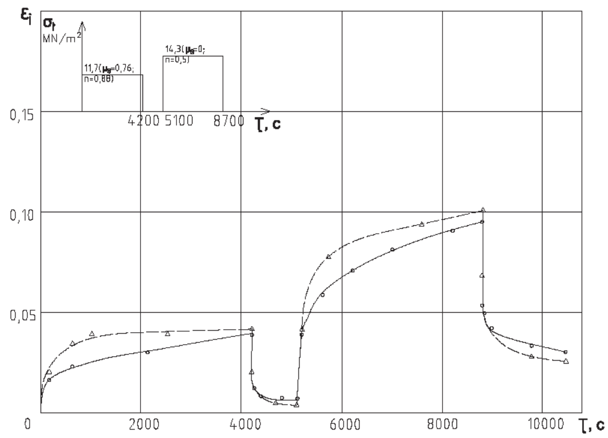

Fig. 8. Disproportional static loading mode and creep curves F-4D:
o – experimental curves; Δ – calculated curves

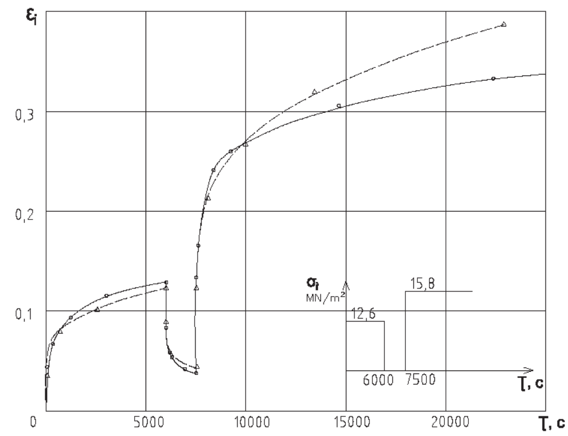

Fig. 9. Non-stationary static loading mode and creep curves F-4 (*n* = 0.5):
o – experimental curves; Δ – calculated curves

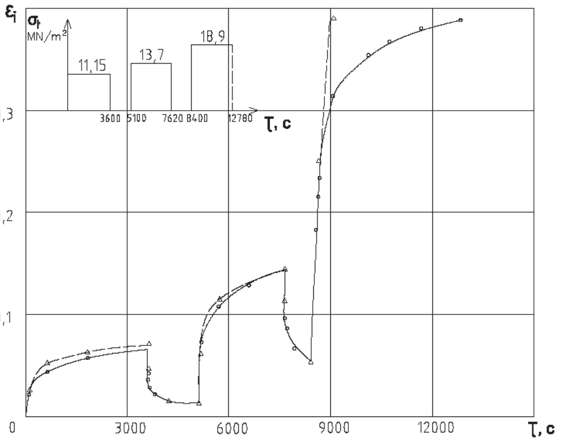

Fig. 10. Non-stationary static loading mode and creep curves F-4 (*n* = 0.5):
o – experimental curves; Δ – calculated curves

Creep under cyclic loading with various frequencies. Fluoroplastics F-4, F-4D, F-4D$_0$ creep under cyclic loading with the frequencies 2.4 Hz, 5.0 Hz and 10.0 Hz were tested in the conditions of maximum per cycle intensity constancy with the cycle asymmetric coefficient $\tau = \sigma_i^{\min} - \sigma_i^{\max} = 0.5$ and temperature 22 ± 1 °C (fig. 14–16). The form of the cycle is sinusoidal. To compare creep complete deformations under static and cyclic loadings, isochronous dependences were made $\sigma_i - \varepsilon_i$ and $\sigma_i^{\max} - \varepsilon_i^{\max}$ while obtaining the creep time $t = 5\cdot10^3$ sec. (fig. 11–13).

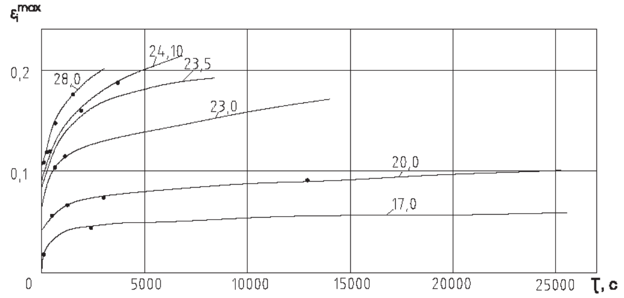

Fig 11. Creep curves F-4 (*n* = 2.8) under cyclic loading with the frequency of 10 Hz

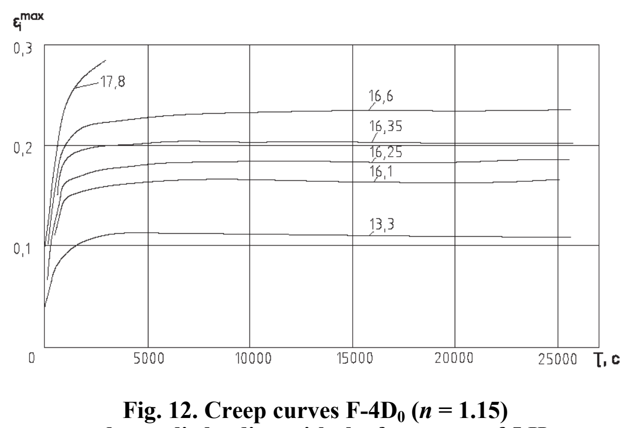

Fig. 12. Creep curves F-4D$_0$ (*n* = 1.15) under cyclic loading with the frequency of 5 Hz

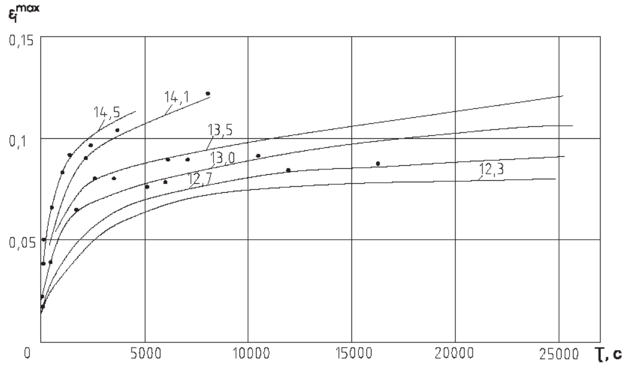

Fig. 13. Creep curves F-4 (*n* = 1.25) under cyclic loading with the frequency of 10 Hz

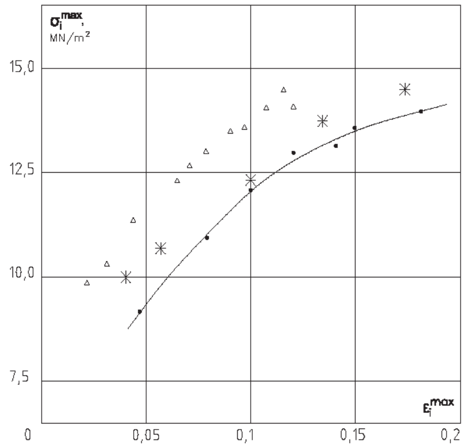

Fig. 14. The maximum stress intensity dependence from the maximum deformation intensity F-4 with $\tau_* = 5000\ sec.$ (*n* = 1.25):
● – f = 0; Δ – f = 10 Hz

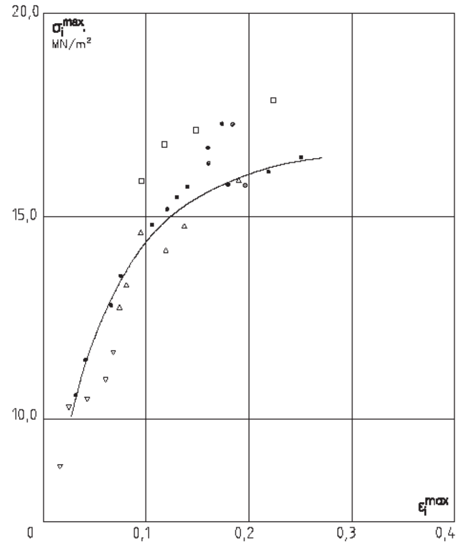

Fig. 15. The maximum stress intensity dependence from the maximum deformation intensity F-4D with $\tau_* = 5000\ sec.$ (*n* = 1.25):
● – f = 0; □ – f = 2.5 Hz; o – f = 5 Hz;
Δ – f = 10 Hz; ∇ – f = 5 Hz with n = 0.88

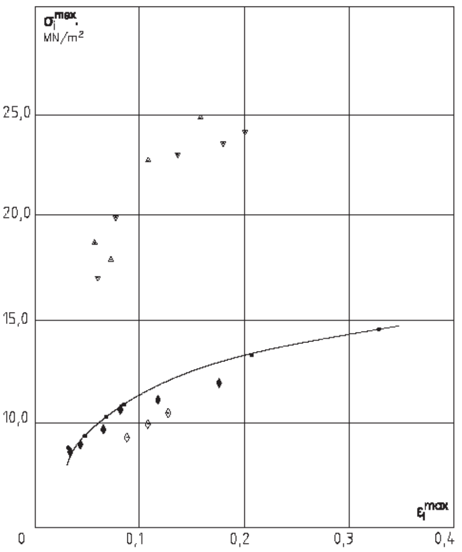

Fig. 16. The maximum stress intensity dependence from the maximum deformation intensity F-4D with $\tau_* = 5000\ sec$. ($n = \infty$):
● – f = 0; ◊ – f = 0 Hz; ♦ – f = 1.2 Hz;
Δ – f = 10 Hz; ∇ – f = 5 Hz with n = 2.8

Thus, experimental points of the same material and type of stress state under frequencies of 2.5 and 5.0 Hz do not completely match to the experimental ones under stationary static loading. It is also noticeable that the material rigidity tends to increase under cyclic loading in comparison with static one, if the maximum variable stress intensity during the cycle equals to the intensity of permanent stresses under stationary loading. Besides, in comparison with static loading and frequencies of 2.5 Hz and 5.0 Hz, under frequencies of 10 Hz there is a significant rigidity increase. The most valuable increase of the material rigidity is when $n = \sigma_x / \sigma_\theta$ is close to $n = \infty$ (linear tension), i.e. under conditions, when under static loading there is the most intensive development of viscoplasic deformations.

The examples of the creep curves under cyclic loading are presented on the fig. 11–13, 17, 18. The nature of the curves differs from one for the static loading. Let us apply for cyclic loading the same equation as for various cases of static loading from the previous section. The instant elastic and instant plastic intensity deformation components are calculated from the maximum stresses per cycle and viscoelastic component is calculated directly by substitution of a variable σ_i values in the equation:

$$\varepsilon_i^{VE} = (a - b\mu_S)\int_0^\tau c\left(\frac{\sigma_{im}+\sigma_{ia}\sin 2\pi f\theta}{\sigma_*}\right)^n k(\tau-\Delta)d\theta. \quad (7)$$

The calculation of the first three complete deformation components does not occur logical issues, but the calculation of viscoplastic component is not so obvious. After drafting series of attempts, the following empirical dependence for that component under cyclic loading was suggested:

$$\varepsilon_i^{\max} = \frac{2(1+\nu)\sigma_i^{\max}}{3E_0\left(1-\frac{\sigma_i^{\max}}{\sigma_{**}}\right)} + \gamma\left[(\alpha-\beta\mu_S)e^{m(\sigma_i^{\max}-\sigma_*)}-1\right] +$$
$$+(a-b\mu_S)\lambda_2 c\left(\frac{\sigma_i^{\max}}{\sigma_*}\right)^n \int_0^\tau \left[A_1 e^{-\frac{\tau}{\mu_1}} + A_2 e^{-\frac{\tau}{\mu_2}}\right]d\theta +$$
$$+(d-l\mu_S)k\left(\frac{\sigma_i^{\max}}{\sigma_*}-\delta\right)\int_0^\tau A_3 e^{-\frac{\tau}{æ}}d\tau, \quad (8)$$

where λ_2 – is an empirical coefficient (for F-4 $\lambda_2 = 0.58$, for F-4D $\lambda_2 = 0.65$, for F-4D$_0$ $\lambda_2 = 0.5$). The calculated according to this equation creep curves are presented on the fig. 20, 21.

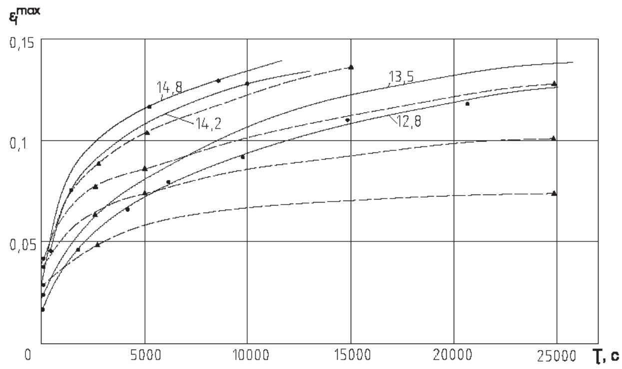

Fig. 17. Creep curves F-4D (n = 1.25) under cyclic loading with the frequency of 10 Hz:
● – experimental curves; Δ – calculated curves

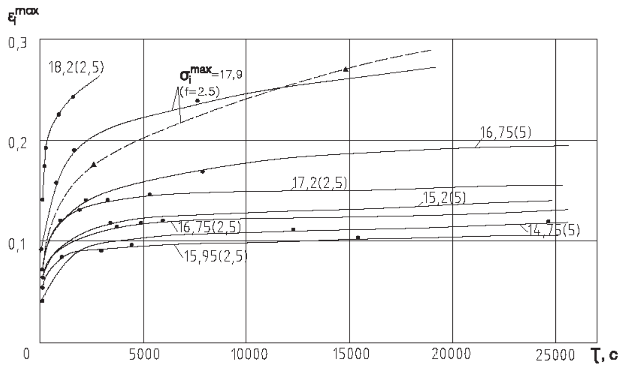

Fig. 18. Creep curves F-4D (n = 1.25) under cyclic loading with the frequency of 2.5 Hz:
● – experimental curves; Δ – calculated curves

Moreover, there was made an attempt to use that empirical dependency also for creep deformation presentation under non-stationary modes of cyclic loading as a several cycle blocks with variable values of $\sigma_i^{\max}$[30].

Discussions. ***Ultimate deformation of fluoroplastics under static and cyclic loading.*** First of all, studying of ultimate deformation is important from an opportunity of formulation some deformation destruction criteria for polymer materials [7]. Experimental data about ultimate material deformation allows to estimate objectively admissible creep deformation of structural elements. For the fluoroplastics in wide range of n there is no ultimate deformation constancy [30]. In whole series of non-stationary loading cases the current deformations ε_i (ε_i^{max}) already reach the ultimate value zone on the first loading steps (fig. 19). That also attests against deformation destruction criteria.

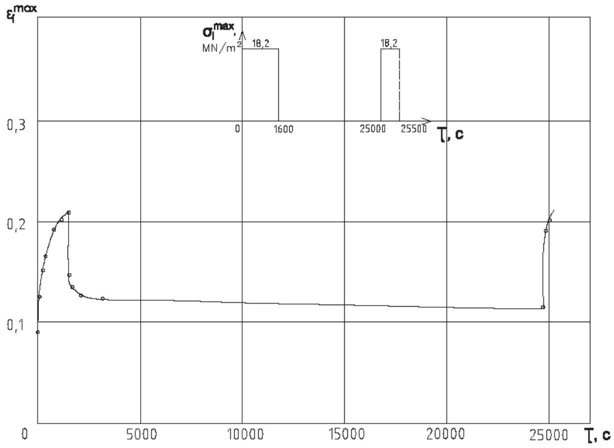

Fig. 19. Creep curves and loading mode (n = 1.25) of cyclic loading with the frequency of 5 Hz

The study of PTFE F-4 sample failure mode is interesting. Under static loading with mostly tensile axial stress the destruction occurs along the transversal section of the tubular sample without visible localization of viscoplastic deformation (with the maintaining the assigned real stress considering the deformation changes). Under biaxial stress state, when n = 1.25, in the destruction place pores occurs, which means that the material is strongly loosened. Sometimes pores occurs in samples under axial tension. Probably, the loosening precedes the sample disruption along the plane of transverse section. Under cyclic loading the same material loosening occurs and only in some cases when n = 1.25 the failure mode differs from described. Under that conditions before the pores appearance a small bubble occurs on the surface of the damaged sample.

Experimental results can be used for estimation of structural elements rigidity.

Conclusion. Creep deformation of fluoroplastics (F-4, F-4D, F-4D$_0$) under stationary and non-stationary loading is satisfactory described by the equation of mechanical states, which considers instant elastic, viscoelastic, instant plastic and viscoplastic deformation components with the use of the volume constancy condition and the condition of stress and deformation deviators similarity. Also that deformations can be described with addition of special parameters, which are functions of the stress deviator form.

The speed of creep under cyclic loading with the constant sign of real stress intensities is lower, than the one under the same static loading when the intensity of permanent stresses σ_i equals to the intensity of the maximum variable stresses σ_i^{max}. Frequency changing from 2.5 to 10 Hz does not cause any significant changing of polytetrafluoroethylene deformation properties, except the case of uniaxial tension with the frequency of 10 Hz, when the increase of the material rigidity occurs, in comparison with other frequencies and $n = \sigma_x / \sigma_\theta$ values during the experiment.

An application of the mechanical states equation, based on results of statistical test results, to the cyclic loading mode gives quite lower results of designed deformation creep values. Thus, an empirical amendment was suggested to that equation of mechanical states.

For fluoroplastics in quite wide range n there is no constancy in ultimate deformations. The current deformations already reach the ultimate value zone on the first stages of loading, however, destruction does not occur. That also attests against deformation criteria of failure.

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About the authors

Ogorodov Leonid – Associate Professor, Candidate of Technician Sciences, Hydraulic and Strength Department, Peter the Great Saint-Petersburg Polytechnic University. *Scientific interests:* polymer and composite materials, material resistance, creep, material ageing, material durability, long-term fracture. *Contact information:* e-mail – L.ogorodov@mail.ru. *eLibrary SPIN-code:* 1514-6380.

Nickolaeva Inna – Associate Professor, Candidate of Technician Sciences, Hydraulic and Strength Department, Peter the Great Saint-Petersburg Polytechnic University. *Scientific interests:* polymer and composite materials, material resistance, creep, material durability. *Contact information:* e-mail – inna4i4n@mail.ru. *eLibrary SPIN-code:* 8949-8906.

Yakovleva Elena – Associate Professor, Candidate of Technician Sciences, Hydraulic and Strength Department, Peter the Great Saint-Petersburg Polytechnic University. *Scientific interests:* polymer and composite materials, material resistance, creep, material ageing, material durability, long-term fracture. *Contact information:* e-mail – helena47@mail.ru. *eLibrary SPIN-code:* 4575-6835.

Fominykh Olga – Master's Degree Student, Construction Mechanics and Structures Department, Peter the Great Saint-Petersburg Polytechnic University. *Scientific interests:* polymer and composite materials, material resistance, creep, material ageing, material durability, long-term fracture. *Contact information:* e-mail – luola94@mail.ru. *eLibrary SPIN-code:* 8237-1707.

Об авторах

Огородов Леонид Иванович – кандидат технических наук, доцент кафедры гидравлики и прочности, Петербургский политехнический университет Петра Великого. *Область научных интересов:* полимерные и композиционные материалы, сопротивление материалов, ползучесть, старение материала, долговечность материала, долговременный разрыв. *Контактная информация:* e-mail – L.ogorodov@mail.ru. *eLibrary SPIN-code:* 1514-6380.

Николаева Инна Павловна – кандидат технических наук, доцент кафедры гидравлики и прочности, Петербургский политехнический университет Петра Великого. *Область научных интересов:* полимерные и композиционные материалы, сопротивление материала, ползучесть, долговечность материала. *Контактная информация:* e-mail – inna4i4n@mail.ru. *eLibrary SPIN-code:* 8949-8906.

Яковлева Елена Леонидовна – кандидат технических наук, доцент кафедры гидравлики и прочности, Петербургский политехнический университет Петра Великого. *Область научных интересов:* полимерные и композиционные материалы, сопротивление материала, ползучесть, старение материала, долговечность материала, долговременный разрыв. *Контактная информация:* e-mail – helena47@mail.ru. *eLibrary SPIN-code:* 4575-6835.

Фоминых Ольга Васильевна – магистрант кафедры строительная механика и строительные конструкции, Санкт-Петербургский политехнический университет Петра Великого. *Область научных интересов:* полимерные и композиционные материалы, сопротивление материала, ползучесть, старение материала, долговечность материала, долговременный разрыв. *Контактная информация:* e-mail – luola94@mail.ru. *eLibrary SPIN-code:* 8237-1707.

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