12. V. P. Golub, A. S. Oleinik, and V. N. Pavlov, "Features of short-term deformation during vibration," Mashinovedenie, No. 5 (1988).

ENERGY VARIANT OF THE UNIAXIAL THEORY OF CREEP AND RUPTURE STRENGTH

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All of the procedural recommendations contained in [1] which pertain to the third stage of creep are based either on strain-hardening theory or on flow theory, and they all have several shortcomings. One deficiency is the impossibility of describing reverse creep during unloading. Ignoring the latter in calculations will lead to errors in finding the time to rupture, particularly under transient and cyclic loads. Another unresolved problem is formulating the governing rheological equations, which make it possible to describe creep beyond the elastic limit. There is also the question of the selection of a fracture criterion that could be used to describe the following experimentally observed facts: the nonmonotonic character of the limiting inelastic strain during fracture; the nonlinear character of rupture-strength curves; the presence of a stage of "avalanche" creep. Thus, in the present study, we want to develop a creep theory and fracture criterion for metals that will allow us to solve the problems just mentioned.

1. We used the method of strain separation as the basis for construction of the corresponding rheological equations. This method has been proposed for the first and second stages of creep [2]. To decribe the third stage, it is customary to adopt a hypothesis in which the damage process is directly connected with the cumulative inelastic strain and the running stress. One characteristic of the state of the material is the damage parameter, which is linked with the relative reduction in the cross-sectional area of the specimen and the consequent increase in the true stress due to microscopic fracture of the material during deformation [3-9].

In the present study, we further develop the energy approach proposed in [10-12] to describe the stage of softening of the material. In accordance with this approach, the damage parameter is assumed to be proportional to the linear combination of the amounts of work done by the true stress on creep strain and on plastic deformation. The main form of the governing equations is as follows

$$\varepsilon = e + e^p + p,\ \dot{e} = \dot{\sigma}/E,\ \dot{e}^p = \varkappa S'(\sigma)\dot{\sigma},\ p = u + v + w,$$

$$u(t) = \sum_{k=1}^{s} u_k(t),\ \dot{u}_k(t) = \lambda_k\left[a_k(\sigma(t)/\sigma_*)^n - u_k(t)\right],$$

$$v(t) = \sum_{k=1}^{s} v_k(t),\ \dot{v}_k(t) = \begin{cases}\lambda_k\left[b_k(\sigma(t)/\sigma_*)^n - v_k(t)\right], & b_k(\sigma(t)/\sigma_*)^n > v_k(t),\\ 0, & b_k(\sigma(t)/\sigma_*)^n \leqslant v_k(t);\end{cases}$$

$$\dot{w}(t) = c(\sigma(t)/\sigma_*)^m; \tag{1.1}$$

$$\sigma = \sigma_0(1 + \omega); \tag{1.2}$$

$$\dot{\omega} = \gamma\sigma\dot{e}^p + \alpha\sigma\dot{p}, \tag{1.3}$$

where ε is the total strain; e and e^p are the elastic and plastic strain; p is the creep strain; u, v, and w are the viscoelastic, viscoplastic, and viscous components of p; σ_0 and σ are the nominal and true stresses; E is the Young's modulus; λ_k, a_k, b_k, c, n, m, σ_* are rheological constants of the material which can be used to describe the first and

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TABLE 1

Material	T, °C	σ_+, MPa	$E\cdot10^{-5}$, MPa	g	h	γ_1, MPa^{-1}	A_*^p, MJ/m^3	m_2
EI 698	750	480,7	1,47	$5,72\cdot10^{-6}$	2,145	$6,93\cdot10^{-3}$	201,2	0
EP 693	750	716,3	1,29	$3,26\cdot10^{-5}$	2,242	$4,53\cdot10^{-3}$	96,6	0
OT 4	500	176,6	0,68	$2,35\cdot10^{-6}$	2,61	$3,24\cdot10^{-2}$	38,94	0

second stages and their irreversible parts; γ and α are material parameters which govern its softening. The value of $\kappa = 1$ at $\sigma(t) > \sigma(\tau)$ $(0 \le \tau < t)$ and $\kappa = 0$ if it becomes possible to indicate the moment when $\sigma(t) \ge \sigma(t)$.

A detailed analysis of the experimental data shows that in the general case $\gamma = \gamma(e^p)$, $\alpha = \alpha(\sigma_0)$, and we can express these functions through power approximations of the form

$$\gamma = \gamma_1 (e^p)^{m_2}, \quad \alpha = \alpha_1 (\sigma_0)^{m_1}. \tag{1.4}$$

For a number of materials, γ = const and α = const in special cases.

2. The time to rupture is usually evaluated using fracture criteria based on strain [5, 7, 13], energy (dissipation) [6, 13, 14], or thermodynamics [15-19] or criteria connected with attainment of a certain critical value by the damage parameters (or functions of these parameters) [8, 20-22]. We will give preference to energy-based fracture criteria, since they permit description of the nonmonotonic character of inelastic strain without particular complication [7, 22-24] while proving very convenient (due to the additivity of different forms of energy) [25].

To predict time to rupture $t = t_*$, we propose the following relation as a criterion

$$\int_0^{t_*} \left(\sigma(t)/A_*^p\right) de^p(t) + \int_0^{t_*} \left(\sigma(t)/A_*^c\right) dp(t) = 1, \tag{2.1}$$

where $A_*^p = A_*^p(T)$ and $A_*^c = A_*^c(T)$ are the critical values of the amounts of work done by the true stress on instantaneous plastic strain and on creep strain. For a fixed temperature, these quantities are material constants. We will show that (2.1) can also be obtained from thermodynamic considerations on the basis of the approach proposed in [15, 16]. In accordance with this approach, fracture of the material occurs when the internal energy density reaches a critical value. Theoretical and experimental studies conducted in [26] suggest that the critical energy density is independent of the loading process and is a material constant.

The internal energy u_+ accumulated in an element of a body being deformed is determined as the sum of two components. Part of this energy is due to the accumulation of the potential (stored, latent) energy u^e in the volumes of the material being deformed (this energy being related to the formation of various defects and serving as a quantitative characteristic of the damage to the material during deformation), while another part is accumulated in the form of heat content u^T. This leads to weakening of the interatomic bonds and, as a result, a physical weakening of the material. Thus, proceeding on the basis of the energy superposition principle [25], we have

$$u_+ = u^e + u^T. \tag{2.2}$$

In accordance with the above, the fracture criterion takes the form

$$u_+(t_*) = u_0 + u_1(t_*) = u_*, \tag{2.3}$$

where $u_0 = u_0(T)$ is the initial value of specific internal energy; u_1 is the increment of internal energy during the time of deformation; u_* is a material constant. The increment $\Delta u = \Delta u_1$ during the time Δt is made up of two components:

TABLE 2

Material	T, °C	σ_*, MPa	s	λ_k, h^{-1}	a_k	b_k	c	n	m	$(MPa)^{-(\alpha_1,(m_1+1))}$	A^c_*, MJ/m^3	m_1
ЭИ 698	750	490,5	1	0,2	$5{,}2\cdot10^{-2}$	$7{,}8\cdot10^{-2}$	$3{,}98\cdot10^{-2}$	3,45	10,96	$3{,}81\cdot10^{-5}$	12,85	—2,59
ЭП 693	750	294,3	2	0,236 2,85	$4{,}53\cdot10^{-2}$ $2{,}74\cdot10^{-3}$	$9{,}48\cdot10^{-3}$ $5{,}74\cdot10^{-3}$	$3{,}25\cdot10^{-2}$	1,06	3,145	4,63	867,2	—0,5
ОТ-4	500	9,81	—	—	—	—	$1{,}29\cdot10^{-5}$	—	3,59	$1{,}18\cdot10^{-2}$	114	0

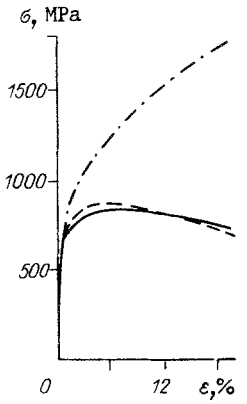

Fig. 1

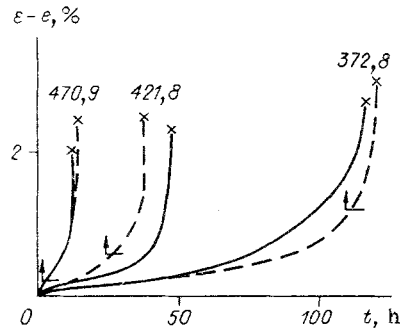

Fig. 2

$$\Delta u_{+} = \Delta u^{e} + \Delta u^{T},\ \Delta u^{e} = \sigma \Delta e^{p} + \sigma \Delta p,\ \Delta u^{T} = \Delta u_{1}^{T} + \Delta u_{2}^{T}. \tag{2.4}$$

Here, in contrast to the work done [6, 14-19, 26], the increment of potential energy Δu^{e} is written not for the nominal stress, but for the true stress σ; Δu_1^T, Δu_2^T is the increment of heat content during plastic deformation and creep. The subsequent problem consists of determining Δu^T. Even under laboratory conditions, direct measurement of this quantity by means of calorimetry is a difficult proposition. It is almost impossible to determine Δu^T by such an approach when evaluating the creep of structural elements under actual service conditions. Thus, we need to find other ways of evaluating Δu^T.

The experimental data in [26] allows us to introduce the following hypothesis: Δu_1^T and Δu_2^T are proportional to $\sigma \Delta e^p$ and $\sigma \Delta p$ respectively. We change (2.4) to the form

$$\Delta u_{+} = \sigma \Delta e^{p} \left(1 + \Delta u_{1}^{T} / \sigma \Delta e^{p}\right) + \sigma \Delta p \left(1 + \Delta u_{2}^{T} / \sigma \Delta p\right). \tag{2.5}$$

Using this hypothesis and the notation $1 + \Delta u_1^T/\sigma\Delta\varepsilon^p = C(e^p)$, $1 + \Delta u_2^T/\sigma\Delta p = D(\sigma_0)$, we write (2.5) in the form

$$\Delta u_{+} = C(e^{p}) \sigma \Delta e^{p} + D(\sigma_{0}) \sigma \Delta p. \tag{2.6}$$

After integrating (2.6), we obtain the below fracture criterion from (2.3)

$$\int_{0}^{t_*} C(e^{p})\, \sigma\, de^{p} + \int_{0}^{t_*} D(\sigma_{0})\, \sigma\, dp = u'(T), \tag{2.7}$$

where $u'(T) = u_* - u_0(T)$. With a fixed temperature in the special case $C(e^p) = C_1 = \text{const}$, $D(\sigma_0) = D_1 = \text{const}$, we find from (2.7) that

$$\int_{0}^{t_*} \left(\sigma / A_{*}^{p}(T)\right) de^{p} + \int_{0}^{t_*} \left(\sigma / A_{*}^{c}(T)\right) dp = 1 \tag{2.8}$$

($A_*^p = u'(T)/C_1$, $A_*^c = u'(T)/D_1$). It can be seen that (2.8) coincides with (2.1).

Thus, criterion (2.1), (2.8) differs from similar criteria in [6, 14-19, 26] in that true stress is introduced both into the constitutive equations and into the fracture criterion. Another difference is that inelastic strain is represented as the sum of plastic strain and creep strain.

3. Let us examine a method of determining the material constants and the experiment needed for this purpose. We use the standard instantaneous stress-strain curve as the initial data to construct plasticity function $S(\sigma)$ and find γ and A_*^p. Despite the known difficulties of obtaining these results for high temperatures, there are sufficiently reliable methods for constructing such curves [27, 28].

Since $p = 0$ in the given case of creep and active loading is taking place ($\dot{\sigma} > 0$), Eqs. (1.1)-(1.3) take the form

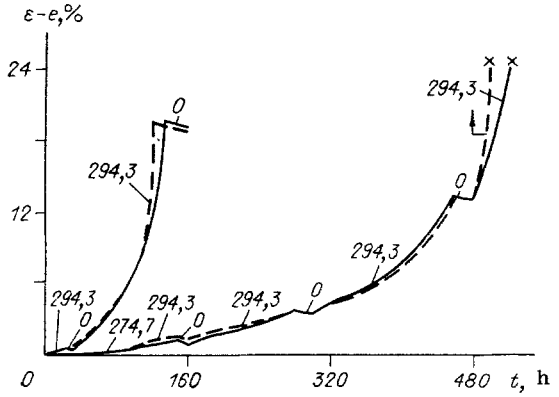

Fig. 3

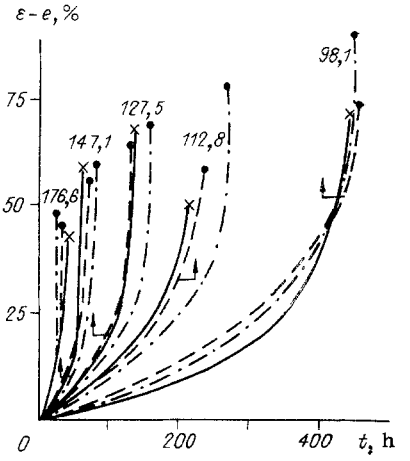

Fig. 4

$$\varepsilon = \sigma/E + S(\sigma),\ \sigma = \sigma_0(1+\omega),\ \dot{\omega} = \gamma\sigma\dot{e}^p. \tag{3.1}$$

We use the initial section of plastic deformation on the stress-strain curve (where e^p should not exceed 1-2%) to determine the form of the plasticity function $S(\sigma)$. Then the smallness of e^p allows us to assume that damage from plastic strain is slight and that $\sigma \approx \sigma_0$. For example, the initial section can be approximated by the power relation

$$e^p = g(\sigma - \sigma_+)^h. \tag{3.2}$$

Here, σ_+ is the proportional limit; g and h are constants that can be determined by the least squares method.

It is easy to use the second and third relations of (3.1) and (3.2) to obtain an expression linking the true σ and nominal σ_0 stresses and the plastic strain function $e^p = \Psi(\sigma_0)$ in implicit form:

$$\sigma = \sigma_0 \exp\left(\gamma_*(e^p)\,\sigma_0\right),\ \gamma_*(e^p) = \int_0^{e^p} \gamma(e^p)\,de^p; \tag{3.3}$$

$$e^p = g\left[\sigma_0 \exp\left(\gamma_*(e^p)\,\sigma_0\right) - \sigma_+\right]^h. \tag{3.4}$$

We solve (3.4) for $\gamma_*(e^p)$:

$$\gamma_*(e^p) = \ln\left[\left((e^p/g)^{1/h} + \sigma_+\right)/\sigma_0\right]/\sigma_0. \tag{3.5}$$

We calculate the parameter $\gamma_*(e^p)$ by means of (3.5) and several experimental points on the instantaneous stress-strain curve (σ_0, e^p), including points on the section corresponding to unstable deformation. Then using the first approximation of (1.4), we find the constants γ_1 and m_2. With p = 0, we find from (2.1) and (3.3) that

$$A_*^p = \int_0^{e_*^p} \sigma\,de^p,$$

where e_*^p is the plastic strain corresponding to fracture of the specimen.

The initial data for finding the parameters of Eqs. (1.1)-(1.3) are steady-state creep curves continued to fracture for several nominal stresses σ_0 lower than the proportional limit.

Let us present an algorithm for calculating the parameters which describe creep.

A. Separating the first and second stages of creep graphically or using more accurate and reliable methods [29, 30], we employ the procedure in [31, 32] to find the

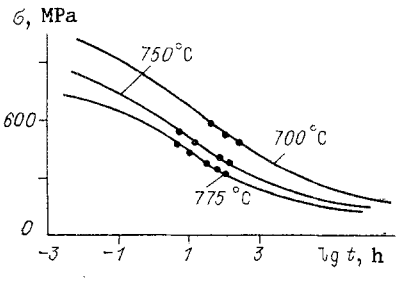

Fig. 5

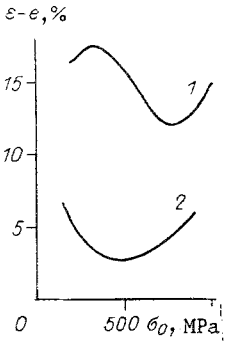

Fig. 6

parameters λ_k, a_k, b_k, c, n, m, σ_*.

B. The quantity $\alpha = \alpha_1(\sigma_0)^{m_1}$ and the constant A_*^c are found from experimental data on steady creep with fixed σ_0 by minimizing the functional

$$\sum_{j=1}^{N} \left[(t_j - t_j^*)/t_j^*\right]^2 \to \min, \tag{3.6}$$

where t_j and t_j^*, respectively, are theoretical and experimental values of time corresponding to the same strain; N is the number of points used in minimization (3.6). For this purpose, we vary α and we perform calculations with (1.1)-(1.3) until we attain the experimental value of inelastic strain corresponding to the moment of fracture $t = t_*$. We then choose the value of α for which condition (3.7) is satisfied. The value of A_*^c is determined from Eq. (2.1):

$$A_*^c = \left[1 - \int_0^{t_*} \left(\sigma/A_*^p\right) de^p\right] \Big/ \int_0^{t_*} \sigma\, dp.$$

C. After we find α and A_*^c for several values of σ_0, we construct the approximation $\alpha = \alpha_1(\sigma_0)^{m_1}$ (the variant α = const is possible in a special case) and we average A_*^c.

4. To check the proposed model (1.1)-(1.4) and criterion (2.1), we conducted a series of tests of alloy EI698 at T = 700, 750, and 775°C, alloy EP693 at T = 700, 725, and 750°C, and alloy EP742 at T = 650 and 750°C. As an example, Fig. 1 shows the result of calculation of the elastoplastic stress-strain curve of alloy EI698 at T = 750°C: the solid line shows the experimental data, the dashed line shows the result calculated from model (1.1)-(1.4) in the coordinates ε–σ_0, and the dot-dash line shows the result in the coordinates ε–σ. Table 1 shows the material constants used to calculate elastoplastic strain for all of the materials studied here. It can be seen from Fig. 1 that the theoretical ε–σ_0 curve is nonmonotonic, with a maximum which corresponds to the theoretical ultimate strength. The curve in the true stresses ε–σ is strictly monotonic. One of the important results obtained here is a theoretical description of the nonmonotonic character of the instantaneous stress-strain curve. As is known [23, 33], it is in this regard that the greatest difficulties are encountered in the approximation.

The dashed lines in Fig. 2 show the result of calculation of the steady creep of alloy EI698 at T = 750°C. The solid lines show experimental data, while the numbers show the stress (in MPa). The rheological constants for this alloy are shown in Table 2. Figure 3 presents an example of the calculation (dashed line) for alloy EP693 at T = 725°C under nonsteady loading. The solid lines show experimental data, while the numbers show the stress (MPa). The material constants are shown in Tables 1 and 2.

Analysis of the theoretical and experimental data showed that reversible creep strain during the third stage is considerably greater than on the initial section. Thus, for the upper realization in Fig. 3, this strain is 3.65 and 5.6 times greater, respectively, for the last unloading stage when determined experimentally and theoretically. The corresponding figures for the lower realization are 3.0 and 2.81. This shows that unloading occurs at the true stress σ rather than σ_0 and indicates that the former increases during deformation.

TABLE 3

σ_0	Q, %			
	—	17,46	12,9	9,5
	t_1^*	t_2^*	t_3^*	t_4^*
	h			
98,1	444	445	356	455,8
112,8	211	265	216	240,1
127,5	141	155	139	137,7
147,1	65	78	83	70,3
176,6	38	26	43	30,1

We used the data in [34] to compare the proposed model (1.1)-(1.4), (2.1) with existing theories. The data in [34] was obtained from creep tests of titanium alloy OT-4 at T = 500°C. The missing parameters for calculating elastoplastic strain were determined from the experimental data in [33], which presented curves of this alloy for T = 20, 100, 200, 300, and 400°C. After these results were analyzed by the method we have proposed, we extrapolated the data for T = 500°C. Tables 1 and 2 show the constants of model (1.1)-(1.4), (2.1) for alloy OT-4 at T = 500°C. The solid lines in Fig. 4 show experimental data obtained for this alloy by different authors. The dot-dash lines show the results calculated from the energy variant [6, 14], while the dashed lines show the results calculated with our model. Table 3 shows values of time to rupture calculated by different authors for this alloy. Here, t_1^* are the experimental results from [34], t_2^* are the results calculated in [6, 14] on the basis of an energy criterion, t_3^* are the results calculated in [7] using a strain criterion, and t_4^* are the results calculated using model (1.1)-(1.4), (2.1). Table 3 also shows the mean relative error $Q_i = \frac{1}{5}\sum_{j=1}^{5}\left|\left(t_{1j}^* - t_{ij}\right)/t_{1j}^*\right| (i=2,3,4)$ of the deviation of the theoretical values of time to rupture from the experimental data for each criterion. It is evident that, on the whole, Eqs. (1.1)-(1.4) approximate the experimental results somewhat better than do the equations from [6, 14], while criterion (2.1) is more accurate than the criteria in [6, 7, 14].

The solid lines in Fig. 5 show typical theoretical rupture-strength curves obtained in accordance with criterion (2.1) for alloy ÉI698. The points show averaged data, while the numbers represent temperatures. It can be seen that the curves are of a distinctly nonlinear character and have a point of inflection. Here, we can tentatively distinguish a straight section and two adjacent sections, three regions characterized by different fracture mechanisms.

Lines 1 and 2 in Fig. 6 show theoretical relations for the limiting elastic strain $\varepsilon^* = \varepsilon^*(\sigma_0)$ for alloy ÉP742 at T = 750°C. It is evident that governing equations (1.1)-(1.4) and criterion (2.1) describe the nonmonotonic character of $\varepsilon^* = \varepsilon^*(\sigma_0)$ with either one or two local extrema. The authors of [6, 8, 22, 23] either described only monotonic relations $\varepsilon^* = \varepsilon^*(\sigma_0)$ or nonmonotonic relations with one local extremum.

We should point out the following interesting fact. Although the stress σ_0 may not exceed the proportional limit, damage accumulation over time causes the true stress σ to become higher than this limit, and instantaneous plastic strain will be superimposed on the creep strain. This event corresponds to the so-called fourth ("avalanche") stage of creep discussed in [35, 36]. The manifestation of this stage was mentioned in [37] from the viewpoint of the mechanics of microscopically nonuniform media. The arrows in Figs. 2-4 indicate the beginning of the avalanche stage of creep, although $\sigma_0 < \sigma_+$ in every case. In contrast to [27], where the technique of determining the beginning of this stage was used only for steady creep curves, the beginning of the avalanche stage can be determined on the basis of model (1.1)-(1.4), (2.1) for any law of stress change. Using this approach also substantiates the physical state of the material at the onset of avalanche creep.

Separation of inelastic rheological strain into plastic strain and creep strain makes it possible to avoid the typical problem of other theories (in which no such distinction is made) which is connected with the need to introduce the hypothesis of a "jump" in internal energy with the transition through a certain value of σ_0 [38]. In fact, there is simply a change in the fracture mechanism, and the first term in (2.1) begins to play an important role.

Thus, proposed model (1.1)-(1.4) and fracture criterion (2.1) make it possible to describe several facts which pose great difficulties from a phenomenological viewpoint.

LITERATURE CITED

1. Strength Calculations and Tests. Theoretical Methods of Determining the Load-Carrying Capacity and Life of Machine Elements and Structures. Method of Determining the Parameters of Creep and Stress-Rupture Curves for Uniaxial Loading. Procedural Recommendations, VNIINMASh, Moscow (1982).
2. Yu. P. Samarin, "Generalization of the method of differentiating strain in creep theory," Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela, No. 3 (1971).
3. Yu. N. Rabotnov, Creep of Structural Elements [in Russian], Nauka, Moscow (1966).
4. L. M. Kachanov, "Time to rupture under creep conditions," Izv. Akad. Nauk SSSR, Otd. Tekh. Nauk, No. 8 (1958).
5. G. F. Lepin, Creep of Metals and Creep-Resistance Criteria [in Russian], Metallurgiya, Moscow (1976).
6. O. V. Sosnin, "Energy variant of the theory of creep and rupture strength," Probl. Prochn., No. 5 (1973).
7. A. M. Lokoshchenko and S. A. Shesterikov, "Method of describing creep and rupture strength in pure tension," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1980).
8. V. I. Astaf'ev, "Damage and fracture criteria in creep," Probl. Prochn., No. 3 (1983).
9. V. N. Kisilevskii, "Variant of kinetic creep equation," Probl. Prochn., No. 1 (1982).
10. V. P. Radchenko, Yu. P. Samarin, and S. M. Khrenov, "Governing equations for materials in the presence of three stages of creep," Dokl. Akad. Nauk SSSR, 288, No 3.
11. Y. P. Samarin and V. P. Radchenko, "Model describing deformation and destruction of metals while stretching them under creepage," Proc. 9th Congress on Material Testing, Budapest, Vol. 1 (1986).
12. Yu. P. Samarin and V. P. Radchenko, "Governing equations for describing the creep and fracture of metals during cyclic creep," Fifth All-Union Symposium. Summary of Documents and Reports. Volgograd, Part 2 (1987).
13. S. A. Shesterikov (editor), Laws of Creep and Rupture Strength: Handbook, Mashinostroenie, Moscow (1983).
14. O. V. Sosnin, B. V. Gorev, and A. F. Nikitenko, Energy Variant of Creep Theory [in Russian], IG SO AN SSSR, Novosibirsk (1986).
15. V. V. Fedorov, "Thermodynamic representations on the strength and fracture of solids," Probl. Prochn., No. 11 (1971).
16. V. V. Fedorov, "Thermodynamic method of estimating rupture strength," ibid., No. 9 (1972).
17. D. A. Kiyalbaev and A. I. Chudnovskii, "Fracture of deformable bodies," Zh. Prikl. Mekh. Tekh. Fiz., No. 3 (1970).
18. A. I. Chudnovskii, "Certain aspects of the fracture of deformable solids," Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela, No. 5 (1969).
19. V. I. Astaf'ev, "Entropy criterion of fracture during creep (growth of ductile cracks)," in: Strength and Reliability of Structures [in Russian], KuAI, Kuibyshev (1981).
20. A. M. Lokoshchenko and S. A. Shesterikov, "Problem of evaluating rupture strength during stepped loading," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1982).
21. A. M. Lokoshchenko and I. V. Namestnikova, "Description of rupture strength for stepped loading," Probl. Prochn., No. 1 (1983).
22. A. M. Lokoshchenko and S. A. Shesterikov, "Model of rupture strength with a nonmonotonic stress dependence of strain during fracture," Zh. Prikl. Mekh. Tekh. Fiz., No. 1 (1982).
23. M. D. Dacheva, A. M. Lokoshchenko, and S. A. Shesterikov, "Model representation of limiting deformation during creep," ibid., No. 4 (1984).
24. V. I. Kovpak, "Methods of predicting the rupture strength and creep of metallic materials for long service lives," Author's Abstract of Engineering Sciences Doctoral Dissertation, Kiev (1979).
25. M. Planck, Principles of the Conservation of Energy [Russian translation], GONTI, Moscow-Leningrad (1938).
26. V. V. Fedorov, Kinetics of the Damage and Fracture of Solids [in Russian], Fan, Tashkent (1985).
27. N. N. Malinin, Applied Theory of Ductility and Creep [in Russian], Mashinostroenie, Moscow (1975).

28. Yu. N. Rabotnov and S. T. Mileiko, Transient Creep [in Russian], Nauka, Moscow (1970).
29. V. I. Kovpak, "Reliable determination of the beginning of the accelerated stage of creep," Probl. Prochn., No. 12 (1973).
30. L. G. Mukhina, "Calculation of creep characteristics from experimental data using the method of nonparametric equalization," in: Theoretical-Experimental Method of Studying Creep in Structures [in Russian], KPtI, Kuibyshev (1984).
31. Yu. P. Samarin, Constitutive Equations of Materials with Complex Rheological Properties [in Russian], KGU, Kuibyshev (1979).
32. Theoretical and Theoretical-Empirical Methods of Determining the Load-Carrying Capacity and Life of Machine Elements and Structures. Theoretical-Experimental Method of Determining Creep and Rupture-Strength Parameters for Nonsteady Uniaxial Loading (1st ed.), Gosstandart, Moscow (1982).
33. O. V. Sosnin and O. O. Sosnin, "On thermoplasticity," Probl. Prochn., No. 12 (1988).
34. O. V. Sosnin and N. G. Torshenov, "Creep and fracture of titanium alloy OT-4 at a constant temperature," Probl. Prochn., No. 5 (1970).
35. M. V. Baumshtein and A. I. Badaev, "Determining the avalanche region of creep," Probl. Prochn., No. 5 (1980).
36. V. V. Osasyuk, "Predicting the residual life of structural elements of power-plant equipment after long use," Author's Abstract of Engineering Doctoral Dissertation, Kiev (1987).
37. V. P. Radchenko and S. V. Kuz'min, "Structural model of damage accumulation and fracture in metals during creep," Probl. Prochn., No. 11 (1989).
38. V. N. Maklakov, "Connection between strength properties and internal energy density during the creep of structures," Creep and Rupture Strength [in Russian], KPtI, Kuibyshev (1986).