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JUSTIFICATION OF THE ENERGY VARIANT OF THE THEORY OF CREEP AND LONG-TERM STRENGTH OF METALS

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The hypotheses underlying the energy variant of the theory of creep and long-term strength of metals are formulated and justified experimentally.

Key words: *creep, fracture, damage parameter, creep stress and strain rate tensors.*

Introduction. Advanced mechanical engineering uses qualitatively new resource-saving forming technologies with varying temperature-rate parameters of the process. Commercial use of unconventional methods of pressure metal working under slow deformation conditions, for which the duration of the process is of significance, requires technological elaboration of approaches to modeling deformation processes. An effective method of increasing the forming accuracy without employing manual working is to use deformation methods based on slow temperature-force actions on metal that have been developed in recent years. In such processes, creep strains make a major contribution to the total irreversible strain. Despite the low deformation rate, these processes have a number of advantages over traditional fast cold and hot forming processes [1]. The working of high-strength, difficult-to-form, and low-plasticity materials involves a number of difficulties due to the fact that in traditional forming methods, the service life of parts may be depleted even at the stage of fabrication. Creep deformation provides larger strains at much smaller forces. A significant increase in the accuracy of part fabrication under creep conditions leads to a decrease in the volume of manual work.

Investigation and modeling of strain-strength features of structural alloys using experimentally justified kinetic equations of creep and damage are of significance in the estimation of the efficiency of structural elements and in the design of technological processes. Rabotnov [2] formulated creep theory for uniaxial stress based on the hypothesis of the existence of the equation of state with a system of differential equations for the parameters describing material structure changes due to damage accumulation from a phenomenological point of view. This theory was called kinetic theory [3]. In [4, 5], a particular variant of creep theory called the energy variant was proposed for the case of a complex stress state with the indication of the underlying hypotheses.

In the present paper, the energy variant of kinetic creep theory is experimentally justified and elaborated.

Basic Hypotheses. In the construction of the energy variant of the theory of creep and long-term strength of metals, the following hypotheses are adopted [5, 6].

1. The material is considered incompressible up to the time of its fracture:

$$\eta_{ij}\delta_{ij} = 0, \qquad i, j = 1, 2, 3 \tag{1}$$

(η_{ij} are the components of the creep strain rate tensor, and δ_{ij} is the Kronecker delta).

Hypothesis (1) has been supported experimentally [6], which allows the components of the creep strain rate tensor to be identified with the components of the deviator of this tensor.

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2. The deviators of the creep strain rate and stress tensors are considered proportional to each other. This hypothesis is equivalent to the law of flow associated with the surface $\sigma_i = \text{const}$:

$$\eta_{kl} = h\,\frac{\partial \sigma_i}{\partial \sigma_{kl}}. \tag{2}$$

Here σ_{kl} are the stress tensor components, $\sigma_i = \sqrt{3s_{kl}s_{kl}/2}$ is the stress intensity, $s_{kl} = \sigma_{kl} - \sigma_0\delta_{kl}$ are the components of the stress tensor deviator, $\sigma_0 = \sigma_{kl}\delta_{kl}/3$ is the hydrostatic component of the stress tensor, and h is a nonnegative function.

Multiplying the left and right sides of (2) by σ_{kl}, performing summation, and taking into account that σ_i is a first-order stress-homogeneous function, we obtain

$$h = W/\sigma_i, \tag{3}$$

where $W = \sigma_{kl}\eta_{kl}$ is the specific dissipation power.

3. It is assumed that there is a functional relation between the intensities of the stress tensor σ_i, creep strain tensor p_i, and creep strain rate tensor η_i; furthermore, in the case of uniaxial stress, this relation becomes the relation between stress, creep strain, and creep strain rate that is used in one of the well-known creep theories. From this assumption, in particular, it follows that for different types of stress state, the presumed functional relation between the corresponding intensities is the same, i.e., the hypothesis of the existence of a unified curve is valid.

Unlike in the traditional approach, the energy variant of creep theory postulates the existence of a functional relation between stress intensity, specific dissipation work A and specific dissipation power W, and $dA = W\,dt$ (t is the current time).

As a measure of the creep process it is proposed to use the specific work instead of the traditionally used strain intensity p_i, and as a measure of the creep intensity, the specific dissipation power instead of the traditionally used rate intensity η_i.

4. Use is made of the concept of the mechanical equation of state proposed by Rabotnov [2], according to which the creep rate of a structurally stable material in a uniaxial stress state at each time depends on the value of the stress applied at this time, temperature, and structural state of the material at the same time.

For a complex stress state, the following formulation of the equation of state is proposed: the creep intensity of a structurally stable material at each time is a function of the stress intensity, temperature θ, and structural state of the material:

$$W = W(\sigma_i, \theta, A, \omega_1, \omega_2, \ldots, \omega_k) \tag{4}$$

($\omega_1, \omega_2, \ldots, \omega_k$ are parameters that describe the change in the structure of the material due to damage accumulation from a phenomenological point of view).

5. According to [2], the parameters $\omega_1, \omega_2, \ldots, \omega_k$ are identified with damage parameters. Next, we will confine ourselves to one parameter, for which the kinetic equation is written as

$$\frac{d\omega}{dt} = F(\sigma_i, \theta, A, \omega), \qquad \omega(x_k, 0) = 0, \quad \omega(x_k^*, t_*) = 1. \tag{5}$$

It is assumed that, in the case of intact material, the parameter ω is equal to zero at all points of the body; if at a point with the coordinates x_k^* at a time $t = t_*$, it reaches a value equal to unity, it is said that fracture occurred at this point, and the time t_* is called the time of onset of fracture of the body.

From (5), it follows that

$$t_* = \psi(\sigma_i). \tag{6}$$

It is obvious that in (6), the stress intensity is a criterion of long-term strength.

The kinetic theory of creep and long-term strength represented by system (1)–(6) has been justified experimentally for a number of metals over a wide range of loads and temperatures under both simple and complex loading.

Justification of the Basic Hypotheses. Experimental studies have been performed for a number of aluminum, titanium, and iron-based alloys under uniaxial tension, compression, pure twisting, and plane stress at stationary and variable external loads over a wide range of temperatures [5–7]. In particular, it has been shown [7] that plots of the specific dissipation work as a function of time t for a number of fixed stresses (uniaxial tension at constant temperature) are geometrically similar, namely: if for some stress σ_k, we have $A = A(t)$, then, for another stress, σ_j, we obtain $A = A(k_j t)$, i.e., by changing the time scale by a factor of k_j, it is possible to reduce curves of the specific dissipation work for various stresses to a unified curve for all stages of material creep, from load application to fracture. It has been established that the coefficient k_j is approximately equal to the ratio of the time of fracture of the sample at stress σ_j to the time of fracture at stress σ_k. Figure 1 shows a unified curve of the specific dissipation work of titanium-base VT9 alloy at a test temperature of 600°C and various stresses under compression and tension.

Figure 2 shows curves of the specific dissipation work for thin-walled tubular samples of St. 45 steel in a plane stress state at a temperature of 450°C; the solid curves in the plane $\sigma - \sqrt{3}\tau$ (τ is the shearing stress) are curves of equivalent stress states, and different points show the stress states at which the experiments were performed. It should be noted that the curves of the equivalent stress states are Mises circles, i.e., $\sigma_i = \text{const}$.

An analysis of the experimental data presented in Fig. 2 leads to the following conclusions:

— the unified curve of the specific dissipation work does not depend on the form of the stress state and is only a function of the stress level and time, i.e., $A = A(\sigma_i, t)$;

— as in the case of a uniaxial stress state, curves of the specific dissipation work are geometrically similar, namely: if for some stress intensity level $\sigma_i^{(k)}$, the relation $A = A(t)$ holds, then, for any other stress intensity level $\sigma_i^{(j)}$, we obtain $A = A(k_j t)$, i.e., by changing the time scale by a factor of k_j, it is possible to reduce the curves of the specific dissipation work for various values of σ_i to a unified curve for all stages of material deformation;

— the similarity coefficient k_j is equal to the ratio of the time of fracture of the sample at a stress intensity $\sigma_i^{(k)}$ to the time of fracture at intensity $\sigma_i^{(j)}$. The fracture times are calculated by formula (6), i.e.,

$$k_j = \psi(\sigma_i^{(k)})/\psi(\sigma_i^{(j)}).$$

Similar unified curves take place for a number of other materials for various stress intensities and temperatures [5–7]. The aforesaid made it possible to concretely define relations (4) and (5) and represent them as

$$\frac{dA}{dt} = \frac{F_1(\sigma_i, \theta)}{U_1(A)U_2(\omega)}; \tag{7}$$

$$\frac{d\omega}{dt} = \frac{F_2(\sigma_i, \theta)}{U_3(A)U_4(\omega)}, \tag{8}$$

where the functional relations F_1, F_2, $U_1, \ldots, U_4$ are determined in experiments. From an analysis of the experimental data given in Figs. 1 and 2 and in [5–7], it follows that at all stages of deformation, from the time of load application to fracture, the specific dissipation work characterizes equivalent states of the material irrespective of the temperature and the level and form of the stress state. This experimental result allows one to identify the specific dissipation work with the damage parameter and, hence, to estimate the measure of the accumulated damage in the material at any time from the amount of the dissipation work. We note that, at the time of fracture, the amount of the dissipation work $A_* = A(t_*)$ does not depend on the temperature and the level and form of the stress state. If one introduces the notation $\omega(t) = A(t)/A_*$, Eqs. (7) and (8) will be identical. Generally [see system (1)–(3), (6)–(8)], the kinetic creep theory is commonly called the energy variant of creep and long-term strength, in which creep of a material and damage accumulation in it are treated as a unified process.

The hypothesis listed tabove have been satisfactorily justified experimentally [5, 6]. In some cases, these hypotheses are not confirmed [5, 6].

Generalization of the Basic Hypotheses. From an analysis of numerous experimental data obtained for a plane stress state, it follows that the flow law associated with the surface $\sigma_i = \text{const}$ is violated. This leads to the necessity of modifying relations (2). We adopt the flow law associated with the surface $\sigma_e = \text{const}$:

$$\eta_{ij} = h\,\frac{\partial \sigma_e}{\partial \sigma_{ij}}.$$

Assuming that the equivalent stress σ_e is a first-order stress-homogeneous function and determining, as above, the function h, we obtain $h = W/\sigma_e$. Hence,

$$\eta_{ij} = \frac{W}{\sigma_e}\,\frac{\partial \sigma_e}{\partial \sigma_{ij}}. \tag{9}$$

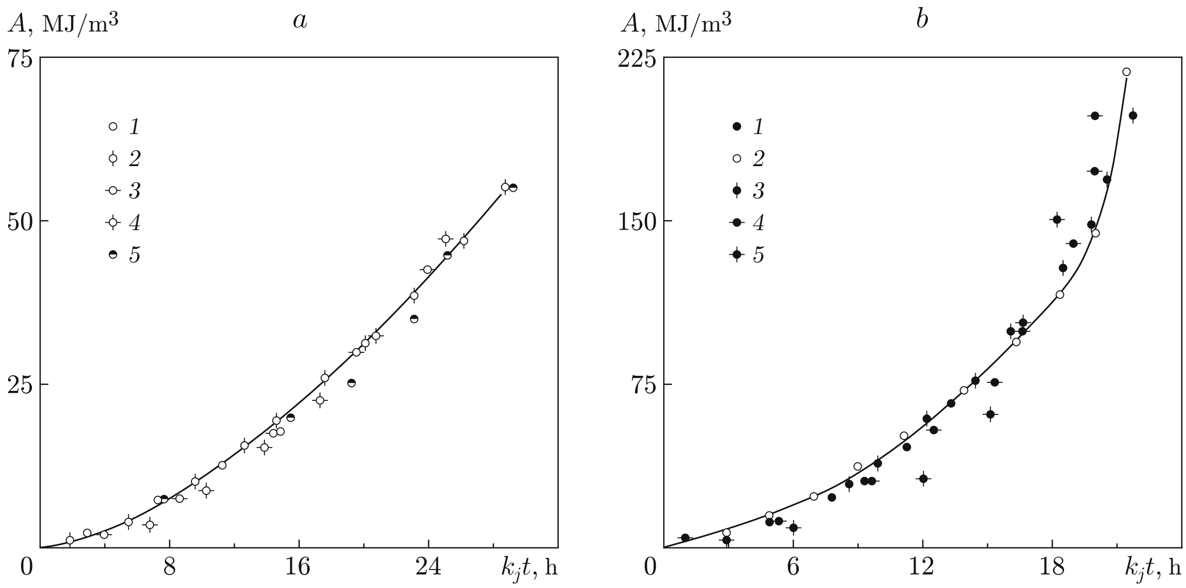

Fig. 1. Unified curve of the specific dissipation work during creep of titanium-base VT9 alloy at a temperature of $\theta = 600^\circ$C and various stresses under compression (a) and tension (b): (a) 1) $\sigma_1 = -150$ MPa and $k_1 = 3.54$; 2) $\sigma_2 = -250$ MPa and $k_2 = 1$; 3) $\sigma_3 = -350$ MPa and $k_3 = 0.28$; 4) $\sigma_4 = -450$ MPa and $k_4 = 0.145$; 5) $\sigma_5 = -573$ MPa and $k_5 = 0.026$; (b) 1) $\sigma_1 = 150$ MPa and $k_1 = 5.6$; 2) $\sigma_2 = 250$ MPa and $k_2 = 1$; 3) $\sigma_3 = 350$ MPa and $k_3 = 0.35$; 4) $\sigma_4 = 450$ MPa and $k_4 = 0.095$; 5) $\sigma_5 = 550$ MPa and $k_5 = 0.033$.

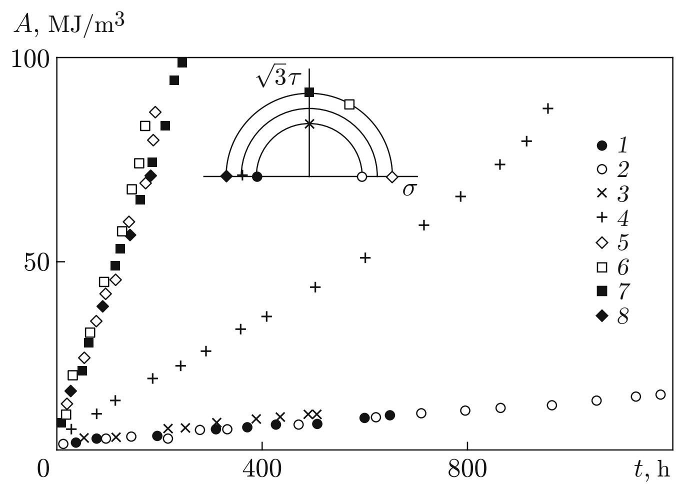

Fig. 2. Unified curves of specific dissipation work during creep of St. 45 steel in a plane stress state at $\theta = 450^\circ$C for stress intensities $\sigma_i = 157$ (1–3), 206 (4), and 235 MPa (5–8): 1) $\sqrt{3}\,\tau/\sigma = -0$; 2) $\sqrt{3}\,\tau/\sigma = \infty$; 3) $\sqrt{3}\,\tau/\sigma = +0$; 4) $\sqrt{3}\,\tau/\sigma = -0$; 5) $\sqrt{3}\,\tau/\sigma = +0$; 6) $\sqrt{3}\,\tau/\sigma = \sqrt{3}$; 7) $\sqrt{3}\,\tau/\sigma = \infty$; 8) $\sqrt{3}\,\tau/\sigma = -0$.

Without loss of generality, we approximate σ_e in the form proposed in [6]:

$$\sigma_e = \sigma_i f(\zeta), \qquad f(\zeta) = [1 + \alpha(\sin 3\zeta)^\lambda]^{1/(2\nu)}. \tag{10}$$

In the deviator plane, the direction of the stress intensity vector is determined by the angle of the stress state ζ. If $f(\zeta) = 1$, the flow law (9) coincides with (2).

In experiments under conditions of a plane stress state, a systematic deviation of the creep strain rate and stress deviator from the proportionality law is observed. This fact has the following geometrical interpretation. The direction of the creep strain rate vector in the deviator plane is characterized by an angle φ, and the direction of the creep strain vector by an angle ψ. Then, the angle $\omega_\eta = \zeta - \varphi$ is a measure of the deviation of the corresponding deviators from the proportionality law. This angle is commonly called the similarity phase (in the terminology of Novozhilov) [2, 6].

An analysis of experimental data [5, 6] on the plane stress state of thin-walled tubular samples loaded by an axial extending or compressing force and simultaneously by a twisting moment or internal pressure leads to the following conclusions.

1. In a stationary stress state and in the case of simple loading [$\zeta(t) = \text{const}$] at any time up to the fracture, $\varphi(t) = \psi(t) \neq \zeta(t)$, if the hypothesis of the similarity of the corresponding deviators is valid (the deviation does not exceed 10% [2]), then, $\varphi(t) = \psi(t) \approx \zeta(t)$.

2. It has been established experimentally that the similarity phase of the corresponding deviators does not depend on the temperature and the level of the stress state and is an odd function of only the angle of the stress state.

Using expressions (10), the tangent of the similarity phase is calculated by the formula [2]

$$\tan \omega_\eta = -\frac{1}{f(\zeta)} \frac{\partial f}{\partial \zeta}.$$

3. In the case of complex loading, the similarity phase of the stress and creep strain rate deviators immediately after the bend of the loading trajectory acquires an increment which depends only on the increment in the angle of the stress state; in other words, $\varphi(t) \neq \psi(t) \neq \zeta(t)$, and there is a deviation of the creep deformation rate vector in the direction of rotation of the stress intensity vector, the deviation being the greater the larger the increment in the angle of the stress state [5]. With time, the increment in the deviator similarity phase tends to zero [5]. This experimental fact necessitated a correction of the functional relation (10) for the equivalent stress. In this case, we assume that $\sigma_e = \sigma_i F(\zeta, t)$ [6]. The structure of the function $F(\zeta, t)$ is such that, in the case of a stationary stress state and simple loading, it is degenerated to $f(\zeta)$, and in complex loading, it tends with time to the function $f(\zeta)$ [6].

The experimental results given above confirm that the hypothesis of the existence of a unified curve in energy variables is reasonable and reveal its advantage over similar hypothesis used in other theories, especially in engineering creep theories. Indeed, in these theories, as noted above, the creep intensity is estimated as the creep strain rate intensity η_i. Then, it is obvious that a measure of creep is the quantity

$$p_i' = \int_0^t \eta_i \, d\tau,$$

which is the well-known Odqvist parameter. However, the primary information indicating the tendency of materials to creep are displacements measured during experiments which are converted to the corresponding components of the creep strain tensor. Therefore, the strain intensity p_i is used as a measure of creep [2–4]. The question of the equivalence of the creep measures p_i and p_i' arises. It is obvious that $dp_i'/dt = \eta_i$ and $dp_i/dt = \eta_i \cos(\varphi - \psi)$. However, the angles φ and ψ of the creep strain rate and creep strain tensors are equal only for a stationary stress state and under conditions of proportional loading. It is only in these loading regimes that the measure p_i equivalent to the measure p_i'.

In the case of complex loading, $\varphi(t) \neq \psi(t)$; therefore it is obvious that the measures $p_i' = \int_0^t \eta_i \, dt$ and $p_i = \int_0^t \eta_i \cos(\varphi - \psi) \, dt$ are not equivalent. This significant disadvantage is eliminated in the energy variant of creep theory since for the creep measures chosen in it and its intensity for any loading path, we always have $dA/dt = W$.

From an analysis of experimental data on long-term strength, it follows that in expression (6), the long-term strength criterion σ_i should be replaced by the criterion

$$\sigma_{e*} = \sqrt{S_2}\, f(\zeta) + \beta\sigma_0, \qquad \beta \geqslant 0 \tag{11}$$

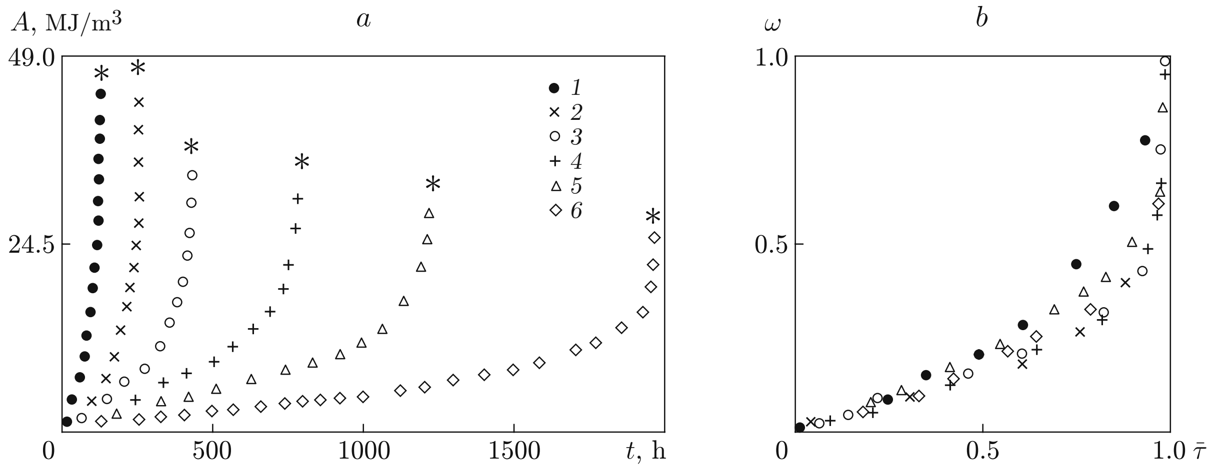

Fig. 3. Curves of the specific dissipation work under creep (a) and the unified curve in the coordinates $\omega - \bar{\tau}$ (b) for OT-4 alloy at $\theta = 500^\circ$C and various tensile stresses: $\sigma = 132$ (1), 113 (2), 98 (3), 93 (4), 88 (5), and 78 MPa (6); asterisks denote the fracture time t_* and the work A_* at the time of fracture of the sample.

($\sqrt{S_2} = \sigma_i/\sqrt{3}$ is the second invariant of the stress tensor deviator). In the case $\beta = 0$, the equivalent stress (11) coincides with the equivalent stress (10).

In [6], a procedure of determining the material constants α, λ, ν, and β is described and the choice of the function $f(\zeta)$ is justified. Without loss of generality, the equation of state (7) and the kinetic equation for the damage parameter (8) can finally be written as

$$\frac{dA}{dt} = \frac{\Phi_1(\sigma_e, \theta)}{U_1(A)U_2(\omega)}, \qquad \frac{d\omega}{dt} = \frac{\Phi_2(\sigma_{e*}, \theta)}{U_3(A)U_4(\omega)}. \tag{12}$$

System (1), (9)–(12), as above, will be called the energy variant of the theory of creep and long-term strength, in which the processes of creep and damage accumulation are accompanying interrelated processes.

From the solution of system (12), it follows that $\omega = \omega(A)$. Only in the case where the specific dissipation work can be identified with the damage parameter ω does system (1), (9)–(12) represent the energy variant of the kinetic theory in which creep and damage accumulation is a unified process; in this case, Eqs. (12) are equivalent.

If the functions U_1, U_2, and U_3 are constants, system (1), (9)–(12) degenerates to a system which corresponds to the Kachanov theory, according to which the creep and damage accumulation are two independent processes.

We note that the energy variant of the theory of creep and long-term strength is still far from completion. For example, the representation of the equivalent stress in the form (10) is not unique. For materials whose creep depends on the form of the stress state, various approximations of the function $f(\zeta)$ are presented in [8–11].

The majority of constructional alloys are significantly anisotropic materials; therefore, the extension of relations (1) and (9)–(12) to such materials with simultaneous development of a procedure for determining material functions and constants is an independent problem.

Let us consider one more experimental result. For a number of modern materials over a wide temperature-time interval (at ageing temperatures, in the region of structural-phase changes), the specific work at the time of fracture can be significantly dependent on the temperature and the level and form of the stress state, i.e., $A_* = A_*(\theta, \sigma_i, \zeta)$. However, curves of the specific dissipation work plotted in the variables $\omega - \bar{\tau}$ ($\omega = A/A_*$ and $\bar{\tau} = t/t_*$), are a unified curve. Figure 3 shows curves of the specific dissipation work in the case of tension for an OT-4 titanium alloy at a temperature of 500°C.

Using the Energy Variant of Creep Theory: Results and Prospects. Supplementing Eqs. (1) and (9)–(12) by equilibrium equations, Cauchy relations, the continuity equation for creep strain rates, and the corresponding boundary conditions, we obtain a closed system to determine the stress–strain state of a solid at any time up to the beginning of its fracture. In other words, the energy variant of kinetic creep theory, as any other of its variants combines two problems, namely, the problem of calculating the stress–strain state of a solid and the problem of calculating the time of onset of fracture into one problem which can be solved by any known method.

In [12], the energy variant of creep theory is used to construct a model of high-temperature creep and to solve the coupled problem of the thermomechanical and thermophysical behavior of the fuel elements of nuclear power reactors in accidents.

We note that the energy variant of the theory of creep and long-term strength has also been used to justify the possibility of hot forming of structural elements of aluminum alloys.

In particular, the results of this justification underlay the development of an automated system for designing, modeling, and electronic testing of the manufacture of doubly curved monolithic panels and the intricate shape of modern aviation products [13–15].

In addition, this energy variant of creep theory has been used to develop a technology which combines hot forming (die forging), hardening heating, and proper thermal hardening (quenching), which made it possible to manufacture the main shaping parts of the BMP-3 infantry armored carrier turret [16].

In conclusion, we note that the energy variant of the theory of creep and long-term strength allows one to calculate the stress–strain state of structural members and simultaneously to estimate, from a phenomenological point of view, not only the used material life but also the remaining life, which is included in the calculation of the additional life of structural members whose specified service life has ended.

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