STRUCTURAL PARAMETERS AND CREEP STRENGTH OF METALS UNDER CREEP CONDITIONS

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1. In describing the process of high-temperature creep of metals, the conception of mechanical equations of state [1] has acquired great acceptance, wherein the creep strain rate tensor $\dot{p}_{ij}$ is determined by running values of the stress tensor σ_{ij}, the temperature T and a set of structural parameters $q_1, q_2, \ldots, q_n$

$$\dot{p}_{ij} = \dot{p}_{ij}(\sigma_{kl}, T, q_1, q_2, \ldots, q_n). \tag{1.1}$$

The change in the structural parameters q_i characterizing the running inner state of the material is described by a system of kinetic equations of the form

$$\dot{q}_i = \dot{q}_i(\sigma_{kl}, T, q_1, q_2, \ldots, q_n). \tag{1.2}$$

Under a definite specification of the parameters $q_1, q_2, \ldots, q_n$ the relationships (1.1) and (1.2) permit the description of different effects of the creep process (hardening, softening, etc.) and the creep strength of metals [1-3]. Rupture criteria based on a certain structural parameter (the damage parameter) reaching its limit value at the time t_* of rupture take account just of the kinetics of the development of such a parameter (1.2) while leaving aside the creep process (1.1) itself.

Different experimental results indicate that the creep and cumulative damage processes are interconnected [1-3]. From the thermodynamic viewpoint there are elements of a single process, energy dissipation. An energetic modification of creep and creep strength theories is developed in [4, 5] in which the specific power of energy dissipation $W = \sigma_{ij}\dot{p}_{ij}$ was chosen as the measure of the creep process intensity and the specific energy dissipation $A(t) = \int_0^t \sigma_{ij}\dot{p}_{ij}dt$ as the measure of the damage. However, identification of the creep and cumulative damage processes occurred by virtue of the specifics of selecting the measure of the damage. Moreover, the balance relationship of the first law of thermodynamics shows that part of A(t) goes towards a change in the internal energy of the body while the rest is dissipated in the form of heat [6]. Consequently, it would not be true to select all of A(t) as the measure of material damage. It is more natural to take the internal energy density $u_0(t)$ as such a measure, for which the kinetic equation is the first law of thermodynamics [7]

$$\dot{u}_0 = \sigma_{ij}\dot{e}_{ij} + \sigma_{ij}\dot{p}_{ij} - q_{i,i}, \tag{1.3}$$

where e_{ij} is the elastic strain tensor and q_i is the heat flux vector. As rupture criterion for the volume element dV_0 we select the condition that its internal energy density $u_0(t)$ reach its limit value u_* which is a constant of the material [8]. Successful application of the energetic rupture criterion in strength of materials (energetic or fourth theory of strength [9]), linear fracture mechanics [10], and fatigue [11] indicates the promise of such a selection.

2. In the empirical approach to the rupture problem from the aspect of the energetic rupture criterion [11], the work ΔA performed on a body is usually determined by the $\sigma-\varepsilon$ diagram and the quantity of heat delivered to the body ΔQ is found by calorimetric measurements. Consequently ΔU = ΔA + ΔQ found at the time of rupture for different test conditions permits confirmation of the correctness of the original hypothesis ΔU = const and finding the limit value u_* for this material.

In the phenomenological approach [8] it is first necessary to make the structural parameters $q_1, q_2, \ldots, q_n$ specific and to formulate correctly the governing relationships (1.1)

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and (1.2). The fundamental structural changes occurring in a metal under creep condition are related to the motion of dislocations and the generation and development of pores [1-3]. The presence of dislocations in a body can be reflected with the use of the dislocation density tensor α_{ij} (α_{kk} = 0) [6], and pore generation and development by using the damage tensor Ω_{ij} [12]. Simultaneous utilization of two tensor variables is fraught with significant complexity for the experimental determination of the parameters of the governing relationships (1.1) and (1.2). Consequently, in place of the tensor Ω_{ij} of its invariants ω that reflects the bulk pore density in the material [12] and is analogous to the magnitude of the plastic loosening of Novozhilov [13] will be used later.

Therefore, to describe the creep process in metals the dependence of the free energy density ψ_0 on the thermodynamic variables e_{ij}, T and the structural parameters α_{ij}, ω must be given as must also the kinetics of the creep process (1.1) and the change in structure (1.2) be described. The structural parameter α_{ij}, in contrast to ω, exerts no influence on the elastic properties of the material, consequently the dependence $\psi_0(e_{ij}, T, \alpha_{ij}, \omega)$ is representable in the form

$$\psi_0 = \frac{1}{2} K(T, \omega)(e_{kk})^2 + \mu(T, \omega) e'_{ij}e'_{ij} - \alpha_V (T - T_0) K(T, \omega) e_{kh} - \\ - cT \ln (T/T_0) + (c - s_{00}(\alpha_e, \omega))(T - T_0) + \psi_{00}(\alpha_e, \omega). \quad (2.1)$$

Here $e'_{ij} = e_{ij} - \frac{1}{3} e_{kk}\delta_{ij}$ is the deviator of the tensor e_{ij}, $K(T, \omega)$ and $\mu(T, \omega)$ are elastic moduli, α_V is the coefficient of volume expansion, c is the specific heat, $\psi_{00}(\alpha_e, \omega)$, $s_{00}(\alpha_e, \omega)$ are the values of $\psi_0(e_{ij}, T, \alpha_{ij}, \omega)$ and $s_0 = -\partial\psi_0/\partial T$ for e_{ij} = 0 and T = T_0, and $\alpha_e = \left(\frac{2}{3}\alpha_{ij}\alpha_{ij}\right)^{1/2}$ is the intensity of the tensor α_{ij}. The first and second laws of thermodynamics [14] result in generalized Hooke's law relationships for the effective stress tensor

$$\sigma_0/(1-\omega) = K(e_{kk} - \alpha_V (T - T_0)), \quad \sigma'_{ij}/(1-\omega) = 2\mu e'_{ij} \quad (2.2)$$

[$\sigma_0 = \frac{1}{3}\sigma_{kk}$ is the global, and $\sigma'_{ij} = \sigma_{ij} - \sigma_0\delta_{ij}$ the deviator part of the tensor σ_{ij}, while $\sigma_e = \left(\frac{3}{2}\sigma'_{ij}\sigma'_{ij}\right)^{1/2}$ is its intensity] and the Planck inequality for the dissipation density

$$D_0 = \left(\frac{\partial\psi_0}{\partial e_{ij}}\right)\dot{p}_{ij} - \left(\frac{\partial\psi_0}{\partial\alpha_{ij}}\right)\dot{\alpha}_{ij} - \left(\frac{\partial\psi_0}{\partial\omega}\right)\dot{\omega} \geqslant 0. \quad (2.3)$$

The presence of pores in the material results in volume creep whose rate $\dot{p}_{kk}$ is proportional to the rate of change of the parameter ω [12], i.e.,

$$\dot{p}_{kk} = c_0\dot{\omega} \quad (2.4)$$

(c_0 is a certain scalar function of e_{ij}, T, α_{ij}, and ω). Taking account of (2.4) and (2.2), we represent the inequality (2.3) in the standard form for thermodynamics of irreversible processes of the product of thermodynamic fluxes $\{\dot{p}'_{ij}, \dot{\alpha}_{ij}, \dot{\omega}\}$ and their conjugate thermodynamic forces $\{\sigma'_{ij}/(1-\omega), X_{ij}, Y\}$:

$$D_0 = \frac{\sigma'_{ij}}{1-\omega}\dot{p}'_{ij} + X_{ij}\dot{\alpha}_{ij} + Y\dot{\omega} \geqslant 0, \quad (2.5)$$

where $\dot{p}'_{ij} = \dot{p}_{ij} - \frac{1}{3}\dot{p}_{kk}\delta_{ij}$ is the deviator of the tensor $\dot{p}_{ij}$; $X_{ij} = -\partial\psi_0/\partial\alpha_{ij}$; $Y = c_0\frac{\sigma_0}{1-\omega} - \frac{\partial\psi_0}{\partial\omega}$. We represent the relationships (1.1) and (1.2) in the form of a linear tensor relation between the forces and fluxes, which taking account of the Onsager reciprocity relationships [15], we write as

$$\dot{p}'_{ij} = c_1\frac{\sigma'_{ij}}{1-\omega} + c_2X_{ij}; \quad (2.6)$$

$$\dot{\alpha}_{ij} = c_2\frac{\sigma'_{ij}}{1-\omega} + c_3X_{ij}; \quad (2.7)$$

$$\dot{\omega} = c_4Y. \quad (2.8)$$

The inequality (2.5) imposes the constraints $c_1 > 0$, $c_3 > 0$, $c_1c_3 - c_2^2 > 0$, $c_4 > 0$ on the functions c_1, c_2, c_3, c_4 dependent on $\sigma_{ij}/(1-\omega)$, T, α_{ij}, and ω. The relationships (2.6) and (2.7) for $\omega = 0$ permit the description of the fundamental regularities of the hardening process during creep under complex stress state conditions [6]. Inclusion of the parameter ω in the composition of the internal variables permits their extension in a natural manner to the case of weakening [8]. The dependence of Y on σ_0 and σ_e emphasizes the influence of both the global and deviator parts of the tensor σ_{ij} on the bulk creep process. The dependence of α_e in Y indicates the definite contribution of the dislocation motion to the process of pore generation and development in a metal.

Assuming [6] that the function c_1, c_2, and c_3 depend only on $\sigma_e/(1-\omega)$ and representing $\psi_{00}(\alpha_e, \omega)$ as $\psi_{00}(\alpha_e, \omega) = k(\omega)\alpha_e^2$, we obtain from (2.7)

$$\alpha_e(t) = \frac{2}{3}\int_0^t c_2\left(\frac{\sigma_e}{1-\omega(\tau)}\right)\frac{\sigma_e}{1-\omega(\tau)}e^{-\frac{(t-\tau)}{t_s}}\,d\tau. \tag{2.9}$$

Approximating (2.8) by the relationship [1] $\dot{\omega} = A\left(\frac{\sigma_i}{1-\omega}\right)^m$, $\omega(0) = 0$, where $\sigma_i = \chi\sigma_e + 3(1-\chi)\sigma_0$ is the equivalent stress [8], we have for $\omega(t)$

$$\omega(t) = 1 - \left(1 - A(m+1)\,\sigma_i^m t\right)^{1/(m+1)}. \tag{2.10}$$

Two characteristic time scales, the "short" time $t_s = \left(\frac{4}{3}kc_3\right)^{-1}$, governing the extent of the hardening process and being a constant in many cases [16], and the "long" time $t_\omega = [A\sigma_i^m]^{-1}$ governing the extent of the weakening process are present in (2.9) and (2.10). As a rule, these times are separated strongly on the time scale. Consequently, for $t \sim t_s$ the influence of ω can be neglected in (2.9)

$$\alpha_e(t) = \frac{2}{3}c_2(\sigma_e)\sigma_e t_s\left(1 - e^{-t/t_s}\right), \tag{2.11}$$

while for $t \gg t_s$ we can write for the hardening stage and a power-law approximation of the function $c_2(\sigma_e) = C\sigma_e^k$

$$\alpha_e(t) = \frac{2}{3}C\sigma_e^{k+1}t_s\left[1 + \frac{t_\omega}{t_s}\frac{1-(1-\omega(t))^{m-k}}{m-k}\right]. \tag{2.12}$$

It follows from (2.12) that $\alpha_e(t)$ that characterizes the reverse creep of the material [6] grows in the third stage of creep [17]. Therefore, the kinetic relationships (2.7) and (2.8) for the structural parameters α_{ij} and ω permit the description of many effects of the creep in both the first [6] and third stages of creep [8].

3. The rupture condition $u_0(t_*) = u_*$, taking the relationships $u_0 = \psi_0 - T\partial\psi_0/\partial T$, (2.1) and (2.2), into account is representable in the form

$$\frac{1}{2K}\left(\frac{\sigma_0}{1-\omega_*}\right)^2 + \frac{\mu - T\frac{\partial\mu}{\partial T}}{6\mu^2}\left(\frac{\sigma_e}{1-\omega_*}\right)^2 + \alpha_V T\frac{\sigma_0}{1-\omega_*} + u_{00}(\alpha_{e*}, \omega_*) + c(T-T_0) = u_* \tag{3.1}$$

[$K\alpha_V^2(T^2 - T_0^2)$ as compared with $c(T - T_0)$ and the influence of the temperature T on K, α_V and c [18] are neglected in writing (3.1)]. The expression (3.1) relates the level of the thermostress state of the body at the time of rupture with its structural state characterized by $\alpha_{e*} = \alpha_e(t_*)$, $\omega_* = \omega(t_*)$.

An estimate of the theoretical strength of the material in shear $\tau_* = \sqrt{2\mu u_*/(1 - T_0\mu'/\mu)} \simeq \sqrt{2\mu u_*(1 - T_0/T_m)}$, obtained under the assumption of linear elastic strain up to the time of rupture at a constant temperature and without a change in structure as well as for the approximation

$$\mu' = \frac{d\mu}{dT} \simeq \frac{\Delta\mu}{\Delta T} \simeq \frac{\mu(T_m) - \mu(T_0)}{T_m - T_0} \simeq -\frac{\mu(T_0)}{T_m - T_0},$$

follows from (3.1) (T_m is the material melting point). Taking into account that

$$\frac{1}{2K}\left(\frac{\sigma_0}{1-\omega_*}\right)^2 \Big/ \frac{\mu - T\mu'}{6\mu^2}\left(\frac{\sigma_e}{1-\omega_*}\right)^2 \sim \frac{\mu}{3K} \sim 0{,}1,$$

and neglecting the contribution from ω_* into $u_{00}(\alpha_{e*}, \omega_*)$, we write condition (3.1) for the isothermal case in the form

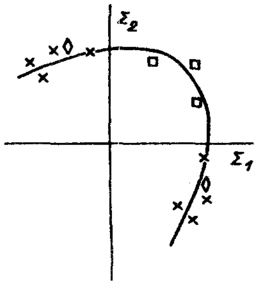

Fig. 1

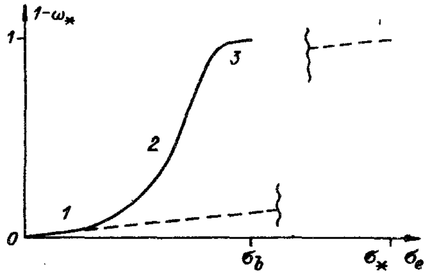

Fig. 2

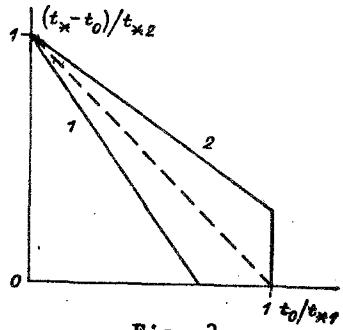

Fig. 3

$$\left(\frac{\sigma_e/\sigma_*}{1-\omega_*}\right)^2+\frac{\sigma_0/S}{1-\omega_*}+\frac{u_{00}(\alpha_{e*})}{u_*}=1. \tag{3.2}$$

Here $\sigma_* = \sqrt{3}\tau_*$ is the theoretical strength of material to rupture, and $S = u_*/\alpha_V T$ is the strength of the material to multilateral breakage.

For a low stress level there results from (3.2) and (2.12) that the rupture condition $u_0(t_*) = u_*$ can be satisfied only because of growth of the parameter ω, which takes on the value $\omega_* \sim 1$ at the time of rupture. The time to rupture t_*, found from (2.10), will be determined by the equivalent stress σ_i:

$$t_* = \left[A(m+1)\sigma_i^m\right]^{-1}. \tag{3.3}$$

The form of the isochronic creep strength curves (the curves $t_* =$ const) on the plane of the principal stresses (σ_1, σ_2) depends on the parameter χ in the expression for σ_i. Figure 1 shows the isochronic curve for $\chi = 0.75$ and the experimental data for a number of steels and alloys obtained in [19] and corresponding to $\chi = 0.75$. The condition $\omega_* \sim 1$ means that the nature of the rupture is determined by the pore generation and development process (brittle fracture by the growth and merger of pores along the grain boundaries [20]).

As the stress level grows, the influence of the third component starts to be felt most substantially in condition (3.2) because of the nonlinear dependence (2.12) of α_e on σ_e. Consequently, we write condition (3.2) for a rise of stress as

$$\alpha_e(t_*) = \alpha_*, \tag{3.4}$$

where α_* is the limit value of the dislocation density tensor intensity. Condition (3.4) means that the nature of the rupture starts to change and be determined by the dislocation slip mechanism (mixed rupture by generation of intergranular microcracks at the juncture of three grains [20]).

For instantaneous rupture, when $t_* = 0$, $\omega_* = 0$ and $\sigma_e \ll \sigma_*$, the strength condition

$$u_{00}(\alpha_{e*})/u_* = 1 - \sigma_0/S, \tag{3.5}$$

analogous to the condition of Novozhilov and Rybakina [9], results from (3.2). It is taken into account in (3.5) that the instantaneous plastic strains are also of dislocation nature and depend on the tensor α_{ij}. The appearance of instantaneous plastic strains in the material is associated with the presence of slip planes therein. Therefore, the nature of the rupture becomes viscous, large irreversible strains resulting in the origination of intergranular shear microcracks [20].

For a given tensor σ_{ij} the relationship (3.2) can be viewed as an equation to find ω_* corresponding to a given stress level at the time of rupture. A schematic graph of the dependence of $1 - \omega_*$ on σ_e is shown in Fig. 2 where 1-3 are the conditional zones of brittle, mixed, and viscous fracture. Condition (3.2) is much too complex for its practical utilization. We select the condition [21]

$$\sigma_e/(1-\omega_*) = \sigma_f \tag{3.6}$$

as a sufficiently simple approximation of (3.2) that reflects all the features listed above for the change in the nature of the rupture for a rise in the stress level, where σ_f is a certain limit stress, generally a function of σ_e or t_* and varying between σ_* (for a low stress level and large times to rupture) to the instantaneous strength limit σ_b for instantaneous rupture.

Expressing the value of ω_* corresponding to this stress level from (3.6), we find the time to rupture from (2.10)

$$t_* = \frac{1-(1-\omega_*)^{m+1}}{A(m+1)\sigma_i^m} = \frac{1-(\sigma_e/\sigma_f)^{m+1}}{A(m+1)\sigma_i^m}. \tag{3.7}$$

When processing experimental data in a narrow range of stress variation, σ_f can be considered constant and it can be found by experimental creep and creep strength results [22]. When extrapolating the experimental data to a broader range of variation of the stress it is necessary to take account of the dependence $\sigma_f(\sigma_e)$ or $\sigma_f(t_*)$ and any of the approximations of these functions can be used.

Integration of the relationships (2.6) with condition (3.6) taken into account permits finding the creep strain intensity $p_e = \left(\frac{2}{3} p'_{ij} p'_{ij}\right)^{1/2}$ at the time of rupture

$$p_{e*}(\sigma_e) = a_s + \left(a_s \frac{t_\omega}{t_s} + \dot{p}_s t_\omega\right) \frac{1-(\sigma_e/\sigma_f)^{m+1-n}}{m+1-n}. \tag{3.8}$$

The method of determining the material parameters A, m, B, n, B_0, n_0, and σ_f for a power-law approximation $\dot{p}_s(\sigma_e) = B\sigma_e^n$, $a_s(\sigma_e) = B_0\sigma_e^{n_0}$, the form of the creep strength curves $t_*(\sigma)$ and the dependence $p_*(\sigma)$ in the uniaxial case as well as an analysis of the experimental creep and creep strength data for a number of steels and alloys are represented in [22].

For a step loading in the uniaxial case the criterion (3.6) describes the deviation from the rule of linear summation of the partial times [1]. Indeed, as the stress σ changes from σ_1 into σ_2 at the time t_0, the damage ω for $t > t_0$ has the form $(1-\omega)^{m+1} = 1 - t_0/t_1 - (t-t_0)/t_2$, where $t_1 = \left[A(m+1)\sigma_1^m\right]^{-1}$ and $t_2 = \left[A(m+1)\sigma_2^m\right]^{-1}$. Replacing t_1 by t_{*1} and t_2 by t_{*2} according to (3.7), we obtain from condition (3.6)

$$\frac{t_* - t_0}{t_{*2}} = 1 - \frac{1-(\sigma_1/\sigma_f)^{m+1}}{1-(\sigma_2/\sigma_f)^{m+1}} \frac{t_0}{t_{*1}}. \tag{3.9}$$

The dependence of $(t_* - t_0)/t_{*2}$ on t_0/t_{*1} for $\sigma_1 < \sigma_2$ and $\sigma_1 > \sigma_2$ (curves 1 and 2) is shown in Fig. 3. It is seen that the curve 1 does not reach the point (1, 0), i.e., growth of the load in the concluding stage of the creep process can result in instantaneous rupture. An analogous effect is described in [13].

In the case of a complex stress state reconstruction of the isochronic creep strength curve occurs from the curve σ_i = const for $\omega_* \sim 1$ (creep rupture at low stresses) to the curve σ_e = const for $\omega_* \sim 0$ (instantaneous rupture) [21]. Such a reconstruction was observed experimentally in [23].

4. Analyzing the energetic rupture criterion as a whole, we turn to (3.1) for the internal energy density. As we see, u_0 is separated into three components, the internal energy density for thermoelastic strain $\frac{1}{2K}\left(\frac{\sigma_0}{1-\omega_*}\right)^2 + \frac{\mu - T\mu'}{6\mu^2}\left(\frac{\sigma_e}{1-\omega_*}\right)^2 + \alpha_V T \frac{\sigma_0}{1-\omega_*}$, the internal energy density associated with the formation of the dislocation structure $u_{00}(\alpha_{e*}, \omega_*)$, and the thermal component of the internal energy density $c(T - T_0)$. For the instantaneous rupture of metals under isothermal conditions the principal part is played by the second component that reflects the multiplication of dislocations occurring during loading and its associated inelastic strain process. The pore development during creep results in a change in the elastic characteristics of the material whereupon the first component starts to be felt and, in a number of cases, even plays the principal part. And finally, a specific kind of rupture, melting, is possible when the third component in the expression for u_0 plays the main part and governs the "rupture" process.

Analyzing other rupture criteria from the aspect of the energetic, it can be noted that microstructural rupture criteria of the type $\omega(t_*) = 1$ or $\alpha_e(t_*) = \alpha_*$ emphasize the importance of the structural changes during rupture. The role and place of the dissipative rupture criterion are seen clearly from the energy conservation law (1.3). The parameter A(t) yields a definite contribution to the total internal energy $u_0(t)$ but it is taken into account completely only for an adiabatic process. For an isothermal creep process, a definite part of A(t) is liberated in the form of heat outward and exerts no influence at all on $u_0(t)$.

Therefore, the internal energy density $u_0(t)$ can be selected as a certain damage macroparameter for a volume element dV_0 that takes account of structural changes occurring in a material, the heat conduction process, etc. By using it the phenomenon of creep strength of metals can be described under creep conditions in the whole range of load variation up to instantaneous rupture. The achievement of $u_0(t)$ in the volume element dV_0 of its limit value u_* denotes rupture of this volume, i.e., the transition of all points of dV_0 from the volume to the surface state. The energetic balance of such a transition is [10]

$$u_0 = u_f + A_f \tag{4.1}$$

(u_f is the internal energy density in the rupture state, A_f is the work of rupture) and permits estimation of the characteristic linear dimension ρ_s of the ruptured volume dV_0. Indeed [8], neglecting u_f as compared with u_* and assuming that all the work A_f goes into the formation of two new surfaces of discontinuity of the displacement dS_0 with surface energy density γ, we have from (4.1)

$$u_* dV_0 = 2\gamma dS_0. \tag{4.2}$$

Estimating $dV_0 \sim \frac{4}{3}\pi\rho_s^3$, $dS_0 \sim \pi\rho_s^2$, we obtain from (4.2)

$$\rho_s \sim \gamma/u_*. \tag{4.3}$$

Assuming γ a new characteristic of the material [10] governing the capacity of the material to resist crack origination together with the stiffness (K, μ), thermal (α_V, c) and strength (u_*, σ_b) properties, the characteristic linear dimension of the ruptured volume dV_0 can be estimated from (4.3). In this case the condition $u_0(t_*) = u_*$ becomes the necessary and sufficient rupture criterion, the condition $u_0 < u_*$ means that all points of the volume dV_0 of characteristic dimension ρ_s would go over into the surface state and a crack dS_0 would be generated in the volume dV_0. The material turned out to be equipped by a "lattice" of the characteristic dimension ρ_s which does not take part in finding the stress–strain state in the unruptured state but determines the scale of spatial discretization with respect to the rupture phenomenon. Experimentally u_* can be determined on smooth specimens but γ (or its related ρ_s) only in specimens with stress concentrators in the time of crack break-out [21] or in the rupture viscosity K_{Ic} [10]. The nature of further crack propagation from the aspect of the energetic rupture criterion is investigated in [21].

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