Radiation aging and creep fracture of metallic alloys

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Abstract

Under the attack of irradiation on metallic alloys the following effects are observed: low temperature and high temperature creep and fracture, irradiation aging and embrittlement. According to the experiments the time to fracture of metallic alloys decreases many times depending on temperature, irradiation dose and aging. These effects are investigated well in the context of physical material science. At the same time, not enough attention is paid to describe the effects integrally by the mechanic of materials methods in the framework of mechanical parameters. In our presentation these methods are applied to describe the radiation creep, aging and fracture of metallic alloys. To formulate the creep fracture law the energy conservation law is applied. Some preliminary calculations are carried out according to the received relations. The theoretical curves of creep and creep fracture for different values of irradiation dose are constructed and they are compared with the corresponding experimental results. These investigations allow to predict the possible variants of creep strain accumulation and fracture of metallic alloys undergoing irradiation.

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Majority of metallic steels and alloys, used in modern industry, in particular, in nuclear power installations are metastable solids inclined to disintegration and formation of the saturated solution and stable particles. Corresponding changes suffer the physical-mechanical properties of the considered materials. Disintegration of solid is substantially accelerated at influence of different physical fields: power, radiation, thermal and other. In totality these processes are known as aging effects [1-5]. In particular, the deformation aging is determined as a depending on time change of properties of materials in the process of deformation and after her. In world scientific literature numerous researches are accumulated on influence of aging processes on the changes of rate of creep, that specify that the processes of the deformation and radiation aging promote the softening of material and to the increasing of the creep rate.

In metallic alloys substantial influence on creep rate at all stages is effected also by the processes of disintegration of solid and formation of secondary phases. These changes of phase composition in the beginning harden material and reduce rate of creep, after there is coagulation of particles of the second phase, which promote softening of material, the increase of creep rate and acceleration of process of failure. Influence of overconcentration of the different defects brought in by anniling and plastic deformation on disintegration of solids is investigated in detail [1]. At the same time more complex problem of radiation disintegration is not studied well. This problem is related to the processes of introduction in material different radiation damages and their influence on kinetics of disintegration of solids taking into account the stages of annealing of defects, accordingly, changes of mechanical properties of materials. As experiments show, these changes can be difficult enough.

In irradiation process the simple and complex complexes of defects including vacancies and inculcated atoms are generated.. Thus part of defects is able to vanish on a opposite type of defects, meeting with dislocations or outcropping. Other part of defects can unite and form pores into a solid. The inculcated atoms can also unite and form the areas of superfluous atomic plane. These processes assist the acceleration of disintegration of solid and, accordingly, change it mechanical properties.

For the account of aging in equation of creep theory we will introduce a variable $\beta = \frac{c_0 - c}{c_0 - c_\infty}$, characterizing the change of volume proportion of hardening phases [6]. Here c_0, c, c_∞ are initial, current and final concentrations of alloying element leading transformation.

Let's define the rate of β phases change by the equation

$$\frac{d\beta}{dt} = (1-\beta) f(\sigma, T, \varphi, t), \tag{1}$$

where T is temperature, σ is stress, φ is dose of irradiation, t is time. At the analysis of experimental data for aging steels and alloys the power approximation $f(t) = k_0 t^n$ (k_0, n are constants) is usually used [1]. In this case the solution of equation (1) at an initial condition $t = 0$, $\beta = 0$ has the form

$$\beta = 1 - e^{-k_1\, t^{n+1}}, \tag{2}$$

where $k_1 = k_0(n+1)$.

Taking into account the marked dependence of creep rate $\dot{\varepsilon}$ on the process of disintegration and considering, in the first approaching, kinetic equation of first-order ($n = 1$) we will introduce, according to the damaged conception [7, 8], the following equation

$$\dot{\varepsilon} = B(T) e^{\phi t} e^{a\sigma} (1-\beta)^{-m}, \tag{3}$$

where a, m are constants, $B = B(T)$, $\phi = \phi(\varphi)$.

In accordance with the relation (3), when β increases the creep rate also increases and when $\beta \to 1$ the creep rate tends to infinity. Such position corresponds to experimental data of the creep rate change on the large time interval of the creep curve.

Considering the case $n = 0$ in relation(2) and introducing it in equation (3) we will get

$$\dot{\varepsilon} = B(T) e^{a\sigma} e^{(\phi+b)t}, \tag{4}$$

where $b = mk_0$.

For the case of constant stress, temperature and constant coefficients and the initial conditions $t = 0$, $\varepsilon = 0$, the solution of the equation (4) will be received as

$$\varepsilon = \frac{Be^{a\sigma}}{(\phi + \mathrm{b})} \left[e^{(\phi+\mathrm{b})\mathrm{t}} - 1 \right]. \tag{5}$$

For comparing to experiments we will use the results of the work [9] on the creep of alloy 03X20H45M4BRC at temperature 650°C. In this paper the experimental creep curves were received at the different levels of stresses 250, 220, 200, 180, 150 *MPa*. On these curves we specified the parameters of equation (5) $B = 9,203 \cdot 10^{-9}$, $a = 0,041$ $[MPa]^{-1}$, $b = 3,1 \cdot 10^{-4}$ $[h]^{-1}$. On Fig. 1 the theoretical creep curve at a value $\sigma = 180$ $[MPa]$ is shown by continuous line (without the account of radiation). Crosses on this curve are mark the selective points of the corresponding experimental creep curve [9]. The dotted line on this figure is show the theoretical curve of creep taking into account radiation according to the formula (5). At calculations on this formula the parameters of equation (5) were specified on experimental creep curves [9], received at stresses 250, 180 *MPa*, and temperature $650°C$ after an irradiation dose $1,1 \cdot 10^{21}\, n/sm^2$. Thus $b = 3 \cdot 10^{-3}\, [h]^{-1}$, and for $\phi = c_1\varphi$ it is found $c_1 = 1,536 \cdot 10^{-40}\, [n/sm^2]^{-1}\, [h]^{-1}$.

The theoretical creep curve (5) using these coefficients is shown on Fig. 1 by dot line. Selective experimental points are corresponding to creep curves of specimen after radiation treatment dose $1,1 \cdot 10^{21}\, n/sm^2$. A good agreement between theoretical and experimental curves is observed.

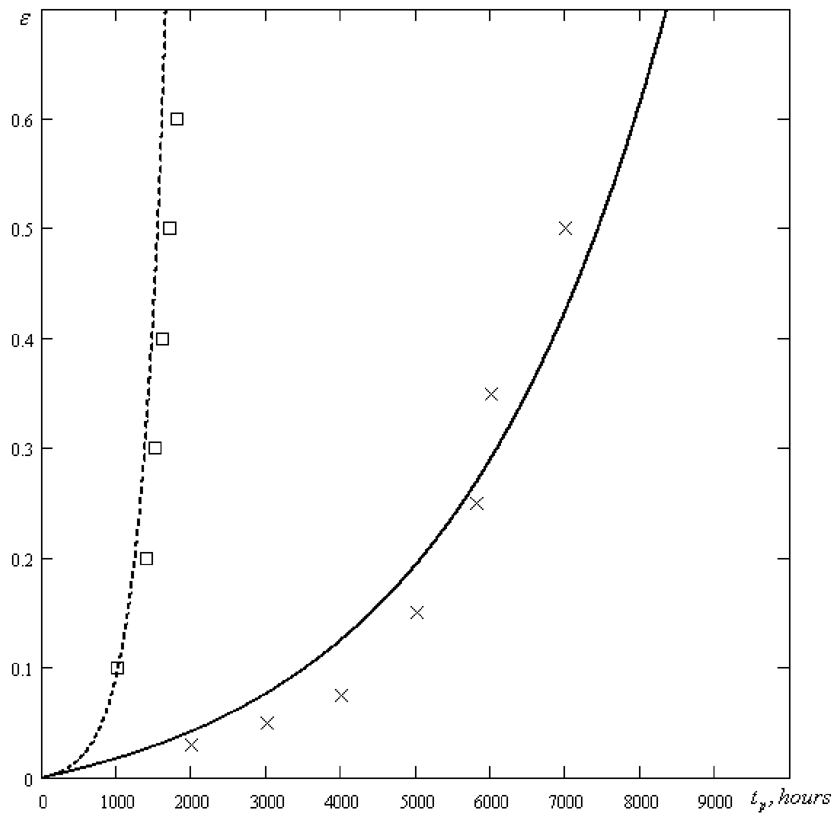

Figure 1: Theoretical creep curves (continuous line - without the account of radiation, dot line - after radiation treatment dose $1,1 \cdot 10^{21}\, n/sm^2$) of alloy 03X20H45M4BRC at temperature $650°C$, $\sigma = 180\, [MPa]$. Points are data from [9].

Let's note that according to the given calculations aging of a material is considered by means of coefficient b. The increase in this coefficient on an order in case of radiation influence indicates considerable acceleration of processes of radiation aging in comparison with deformation aging.

Taking into account the received relations and the first thermodynamics law the of creep strength criterion can be formulated. Applying to the considered problem of deformation and fracture of metallic materials in the conditions of creep radiation the first law of thermodynamics can be formulated as follows. When the specimen is passed from initial condition (initial loading) to final state (specimen failure) a small increment of internal energy of system du is equal to the sum of increments of work δw made over the system (deformation work), heat δq taken away from system and increment of radiation energy δR

$$du = \delta w - \delta q + \delta R, \tag{6}$$

where $\delta w = \sigma_{ij} d\varepsilon_{ij}$ ($d\varepsilon_{ij} = \dot{\varepsilon}_{ij} dt$) is density of mechanical work made dy force acting on an element of media, σ_{ij} are components of stress tensor, $d\varepsilon_{ij}$ are components of strain increment tensor.

Integrating (6) from initial (the corresponding values are marked by index 0) to the fracruted state (the corresponding values are marked by index *). Then from (6) we will have

$$\Delta u_* = w_* - \Delta q_* + \Delta R_*, \tag{7}$$

where

$$\Delta u_* = \int_{u_0}^{u_*} du = u_* - u_0,\ w_* = \int_0^{w_*} \delta w,\ \Delta q_* = \int_{q_0}^{q_*} \delta q,\ \Delta R_* = \int_{R_0}^{R_*} \delta R. \tag{8}$$

Introducing notations $\Delta q_* = w_{*1}$, $\Delta u_* = w_{*2}$, $\Delta R_* = w_{*3}$, the energy conservation law (7) can be written as $w_* + w_{*3} = w_{*1} + w_{*2}$, where w_* is full work of deformation consisting of heat w_{*1}, radiation w_{*3} and latent w_{*2} [10, 11] components of energy.

For pure tension $\varepsilon_{ij} = \varepsilon$, $\sigma_{ij} = \sigma$, $\sigma = const$, the deformation energy can be calculated using the formula $w_* = \sigma\varepsilon_*$, form which follows

$$\varepsilon_* = \frac{w_*}{\sigma} = \frac{w_{*1} + w_{*2} - w_{*3}}{\sigma}. \tag{9}$$

Comparing creep deformations $\varepsilon = \varepsilon_*$ at the time of fracture $t = t_p$ in relations (5), (9), we will receive the corresponding creep strength criterion

$$t_p = \frac{1}{\phi + b} \ln\left[1 + \frac{(\phi + b)(w_{*1} + w_{*2} + w_{*3})}{B\sigma e^{a\sigma}}\right]. \tag{10}$$

Creep strength criterion without the account of radiation and aging was considered earlier in papers [12, 13].

As calculations show the criterion (10) is well describe the qualitative picture of creep fracture processes of metallic alloys with the account of radiation and without radiation. The corresponding curves of creep strength are shown on Fig. 2: with the account of radiation (curve 1) and without radiation (curve 2).

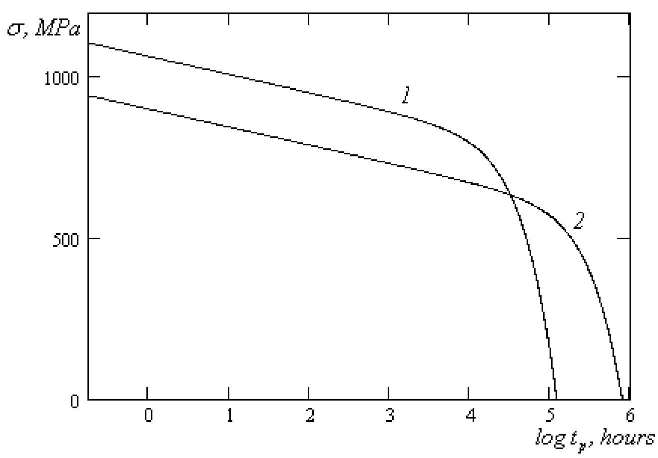

Figure 2: Creep strength curves with the account of radiation (curve 1) and without radiation (curve 2).

When plotting curves 1 and 2 the following values of coefficients were used: $a = 0,041$, $B = 9,203 \cdot 10^{-9}$, $c = 1,536 \cdot 10^{-40}$, $\phi = 1,536 \cdot 10^{22} [n/sm^2]$, $b_2 = 3 \cdot 10^{-4}$, $w_{*2} = 10^8 [J/m^3]$, $w_{*3} = 8 \cdot 10^{10} [J/m^3]$. These values are agreed with the various publications [9, 14, 15].

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