# SIMULATION OF CREEP CRACK GROWTH UNDER THE ACTION OF NEUTRON IRRADIATION

IRYNA DOLINSKA[1], OREST SVIRCHEVSKYI[2]

1. Karpenko Physico-Mechanical Institute of NAS of Ukraine
2. Ivan Franko Lviv National University

A mathematical model is proposed for estimating the period of subcritical growth of a high-temperature creep crack in materials subjected to neutron irradiation and long-term static loading. The model is based on the energy approach regarding the balance of energy components and the balance of the rates of change of energy components. By presenting the creep rate as linearly dependent on the irradiation dose, a new differential equation of high-temperature creep crack propagation in metals is obtained, taking into account the intense influence of irradiation. The residual durability of a through-crack plate made of 304 steel was evaluated.

*Keywords:* neutron irradiation, creep crack, mathematical model, residual lifetime

**Introduction**. The problem of ensuring the reliable operation of nuclear reactors is becoming more and more urgent, since the aging of equipment (internal components) significantly exceeds the pace of technical equipment. Therefore, to reliably predict the failure of such objects (possible accidents), the problem of determining their residual resource arises. Based on the energy approach in fracture mechanics, the method of predicting crack propagation in structural elements that are under the influence of high temperature, static load, and neutron irradiation is described.

**Statement of the problem and method of its solution.** Consider a plate with a rectilinear macroscopic crack of length $l_0$, which is under the influence of long-term static loads $p$. The plate is heated uniformly to the temperature $T_0$ and is irradiated by a flow of neutrons with an intensity $\Phi_0$. The task is to find the period $t = t_*$ subcritical crack growth - the residual durability of the plate.

To solve the problem, we will build a calculation model based on the energy approach [1]. According to the results of work [1], to determine the rate of crack growth, we write down the equation

$$\frac{dl}{dt} = \left[\frac{dW(t,\Phi_0)}{dt}\right]_{t=t_C} \Big/ \left(\gamma_f - \gamma_t\right), \tag{1}$$

with initial and final condition

$$t = 0,\ l(0) = l_0\ ;\ t = t_*,\ l(t_*) = l_0\ , \tag{2}$$

where $W(t,\Phi_0)$ – part of the energy of plastic deformation spent on plastic deformation at a constant crack length during the incubation period $t = t_C$ preparation of her jump depends on time $t$, neutron fluence $\Phi_0$ (the value of the fluence at a unit moment of time) and is generated by the body itself; $\gamma_f = \sigma_t \delta_C$ – specific fracture energy during crack propagation; $\gamma_t = \sigma_t \delta_t (t,\Phi_0)$ – specific energy of plastic deformation in the prefracture zone near the crack tip, $\sigma_t$ – veraged stress in the prefracture zone, $\delta_{It}$ – opening of the crack tip.

The amount of plastic deformation energy, taking into account the results of work [1], is given as follows:

$$W_{pl}^{(2)}(t,\Phi_0) = \alpha\sigma_t \left[\delta_t(0) + \dot{\delta}_t(\Phi_0)t\right]^2 , \tag{3}$$

where $\dot{\delta}_t(\Phi_0)$ – is the rate of opening of the crack tip, which depends on the fluence $\Phi_0$.

High-temperature creep of materials under the influence of neutron irradiation is accelerated due to defect formation and the phenomenon of radiation swelling of the metal [2]. Therefore, based on the results of work [2], in a wide range of stresses, the rate of steady creep can be written by the following linear dependence

$$\dot{\varepsilon}_t(\Phi) = \dot{\varepsilon}(0)(1 + \alpha_\Phi \Phi(t)) ,$$

where $\alpha_\Phi$ – a constant that determines the degree of influence of irradiation on creep; $\Phi(t) = \Phi_0 t$ – the number of neutrons that hit the plate through a unit surface.

Since for a macrocrack the maximum deformation in the pre fracture zone near its tip is proportional to the maximum opening, then in the region of steady creep we can consider a fair dependence

$$\dot{\delta}_t(\Phi) = \dot{\delta}_t(0)(1 + \alpha_\Phi \Phi(t)) . \tag{4}$$

Equation (1) includes the amount of time the incubation period of the preparation of the elementary jump of the high-temperature creep crack. To find it, we believe that the further propagation of the crack occurs when the value is reached $\delta_t(t,\Phi_0)$ the maximum permissible value of opening in the zone of fracture $\delta_C$, as a result, we get the equation

$$\delta_C - \delta_t(0) = \dot{\delta}_t(0) t_C [1 + \alpha_\Phi \Phi_0 t_C]. \tag{5}$$

Solving it with respect to the value $t_c$, we will get

$$t_C = \frac{-\dot{\delta}_t + \sqrt{\dot{\delta}_t^2 + 4\dot{\delta}_C \alpha_\Phi \Phi_0 (\delta_C - \delta_t)}}{2\dot{\delta}_t \alpha_\Phi \Phi_0}. \tag{6}$$

For small values $\alpha_\Phi$, $\Phi_0$, formula (6) can be written as follows

$$t_C = (\delta_C - \delta_t)/\dot{\delta}_t. \tag{7}$$

Taking into account ratios (3), (4), (7), equation (1) will take the form

$$\frac{dl}{dt} = \frac{2\alpha\dot{\delta}_t(0)}{1 - \delta_t/\delta_{IC}(\Phi(t))} + 4\alpha\alpha_\Phi \Phi_0 \delta_{IC}(\Phi(t)). \tag{8}$$

For the case of a macrocrack, when equalities hold $\delta_t = K_I^2/(\sigma_t E)$, $\delta_t/\delta_{IC} = (K_I/K_{IC})^2$, $2\alpha\dot{\delta}_t(0) = A_{2t}(K_I/K_{IC})^{2m}$ [1] equation (8) will take the form

$$\frac{dl}{dt} = \frac{A_{2t}(K_I/K_{IC}(\Phi(t)))^{2m}}{1 - (K_I/K_{IC}(\Phi(t)))^2} + 4\alpha\alpha_\Phi \Phi_0 K_{IC}^2(\Phi(t))/(\sigma_t E) \tag{9}$$

under initial and final conditions

$$t = 0,\ l = l_0; \quad t = t_*,\ l(t_*) = l_*; \quad K_I(l_*) = K_{IC}. \tag{10}$$

Here $A_{2t}, m$ characteristics of high-temperature creep of the material, which are determined from the experiment; $K_I$ – stress intensity factor; $K_{IC}$ – characteristic of material crack resistance; $E$ – Youngs modulus.

**Assessment of the period of subcritical crack growth.** Calculation model (9), (10) was applied to determine the residual durability of a plate with a macroscopic crack length $2l_0$, which is under the influence of neutron irradiation, high temperature and tensile load $p$. Irradiation of the plate with fluence $\Phi(t)$ damages the structure of the metal, which in turn leads to a change in its mechanical properties. The calculation was performed (Fig. 1) for a plate made of steel 304 for a fixed value of crack resistance $K_{IC} = 350$ MPa·m$^{1/2}$, and other data are taken from works [257, 294]: $m = 2{,}2$; $\alpha_{\Phi} = 4{,}2 \cdot 10^{-20}$ sm$^2$/n; $\Phi_0 = 0{,}9 \cdot 10^{21}$ n/sm$^2$; $A_{2t} = 2{,}5 \cdot 10^{-7}$ m/hour.

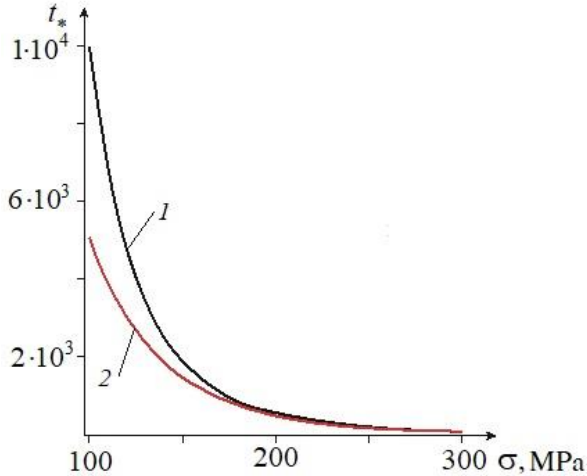


Fig. 1. Plate durability for an analogue of the Griffiths problem: curve *l* – without irradiation; curve *2* – taking into account exposure.

As can be seen from fig. 1, the residual lifetime of a plate irradiated with a neutron beam (curve 2) is lower than that of a plate that was not exposed to irradiation (curve 1). This graphic dependence also illustrates that with increasing load, the influence of neutron irradiation on residual life time decreases. This can be explained by the reduction of the radiation dose, since the time of irradiation of the plate before destruction is also reduced.

**Conclusions.** A calculation model was built for evaluating the influence of neutron irradiation (fluence) on the residual durability of structural elements with high-temperature creep cracks


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