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NUMERICAL MODELING OF HIDDEN DAMAGE ACCUMULATION DUE TO RADIATION EXPOSURE AND HYDROGEN EMBRITTLEMENT

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An approach that allows using the qualitative results of the analysis of the so-called "mechanism based" evolution equations, i.e. constructed using experiments at the micro- and meso-level, to determine the structure of the equation for another, similar in composition, material, is proposed. To determine damage due to irradiation influence, the classical method of Continuum Damage Mechanics was used. The proposed approach of qualitative reproduction of the effects of damage accumulation was used due to the lack of experimental data on the long-term behavior of the material under consideration (steel 08X18N9T) under the given conditions of temperature and radiation exposure. The previously studied influence of the effects of various processes on the hidden damage accumulation was used to reproduce it in the proposed equation. The influence of the type of stress state due to the invariants of the stress tensor and deviator is taken into account. The effect of hydrogen embrittlement is reflected using known data from experiments performed at the macro level, taking into account changes in the modulus of elasticity. The resulting function entered the evolution equation in an exponential form. The developed evolution equation for the damage parameter is added to the previously proven method and software for modeling structural elements exposed to thermal, force and irradiation fields. Examples of the analysis of problems of deformation, damage and fracture of specimens and a tube with a hole, in which the behavior of the corresponding zones of the reactor baffle is simulated, are provided. The performed numerical calculations showed the possibility of practical assessment of the deformed state and the level of acquired hidden damage.

INTRODUCTION

The issues of analyzing the processes occurring in the materials of the nuclear reactor vessel internals (RVI) in order to analyze the level of their deformation and the possibility of damage and macroscopic defects are in the center of the research activities. It is related to the need to ensure the reliability and safe operation of reactors. Investigations in this direction are carried out using the approaches of both Radiation Material Science and Solid Mechanics. In the latter case, the construction of calculation models intended for the evaluation of long-term behavior under a complex stress state is impossible without using the results of Material Science research. The latter, in the form of experimental results, are used to construct constitutive equations, that is, functional dependencies between the components of strain tensors (or their rates) and stresses [1]. As a rule, for this, the results of studies of physical and mechanical characteristics of materials performed using specimens cut from the material (macroscopic level) are used [2]. But in recent years, there have been effective attempts to construct constitutive and evolution equations using the results of Material Science research at the meso-level (see, for example, [3–5]). Construction and subsequent verification of such equations is one of the most important tasks in mathematical modeling of thermophysical, mechanical, and radiation processes [1]. Successes obtained in the mathematical and computer modeling of these processes using the Finite Element Method (FEM) and time integration methods [1, 6–8] allow us to assert that it is effective for this class of problems. In the following sections of the review, attention will be focused on the approaches and the methodology of constructing constitutive equations using already obtained and published experimental results.

During operation of the reactor, thermal and irradiation creep, irradiation swelling, hydrogen embrittlement, damage due to irradiation, and other effects may develop in the RVI structural elements [2]. To model these processes, it is necessary to build constitutive equations that allow accurate and efficient determination of displacements, strains, and stresses (and sometimes other parameters, such as the damage parameter) at each time step. For this, it is necessary to use and generalize the results of experimental research. If there are no financial and time opportunities for conducting experiments, then data obtained by other researchers are used. They are described in special report-type literature like [2] and in scientific publications.

Let us focus on the consideration of the behavior of materials and RVI elements at average operating temperature conditions, which are typical for reactors of the WWER type. This class of structures needs to be taken into account in calculations of irradiation creep, swelling strains and accumulation of hidden damage due to irradiation and hydrogen embrittlement.

A large-scale study of the properties of 304L steel, which is close to 08X18N10T steel and uses as a material for the reactor baffle, was carried out by researchers of the University of Urbana-Champaign and described in [9]. The physical and mechanical properties of steel, obtained with and without taking into account the effect of irradiation on them, are given. Approaches to determining the possibility of steel fracture in a reactor that has operated for 60 years are considered. In [10], the fracture of austenitic stainless steel 08X18N10T irradiated with neutrons is considered. The steel was tested at 320 °C using several experiments representing different crack initiation and growth conditions. It is emphasized that without irradiation, the so-called IASCC (irradiation assisted stress corrosion cracking) damage did not occur in the steel, but areas of intercrystalline fracture, typical of the IASCC phenomenon, appeared on the irradiated specimens. In [11], it is also emphasized that type 304 steels are susceptible to damage due to IASCC.

In connection with the described possibilities of failure during long-term operation of structural elements made of steel type 08X18N10T, it is necessary to consider ways of describing the various processes that occur in them, in order to offer an effective method of calculation. The description of irradiation creep, due to the linearity of the relationship between the strain rates and stresses [1], does not present difficulties if there are appropriate calculation methods.

Description of the irradiation swelling is a more complicated problem. Many investigations have been devoted to the study of the processes that take place in these materials and methods of their mathematical description (regarding the considered materials, see, for example, [12]). To describe irradiation swelling strains, two main approaches are used [12]: the first is more characteristic for experimenters who use least squares methods to describe the obtained data in the full range of all parameters. The second one uses the results obtained by the first approach to construct equations that can be used in modelling the stress-strain state. Such representations are used both for the components of the strain tensor and for their rates. The last approach is more justified from the point of view of the theories of plasticity and creep [13].

The processes of hydrogen embrittlement [14] of the RVI materials during long-term operation are among the worst studied, and the methods of their modelling are only being developed. This is certainly related to the fact that obtaining data on physical and mechanical properties during long-term deformation is a difficult task. Let us consider the main results that have been obtained in recent times in Material Science research [2, 15–22].

The influence of the strain rate on the tensile strength, location of dislocations, deformation and fracture mechanisms of hydrogen-charged austenitic stainless steel AISI 316L was investigated in [15]. It was established that the hydrogen embrittlement index decreases with an increase in the strain rate. It is shown that the hydrogen embrittlement of the material significantly decreases from the surface to the middle of the tested specimens. A decrease in the modulus of elasticity in the crushed specimens is also noted.

The combined effect of neutron irradiation and hydrogen absorption on the mechanical properties and failure modes of steels used for reactor elements was studied by H. Takaku and H. Kayano [16]. The change in tensile properties and failure modes is reasonably explained by the interaction of irradiation defects with hydrogen atoms. It is emphasized in [17, 18] that the process of hydrogen diffusion is strongly influenced by the distribution of stresses and irreversible strains. The important influence of thermal processes is emphasized. It is noted [18] that the duration clearly affects the concentration of hydrogen accumulated in the WWER-440 nuclear reactor during its operation.

The authors of [19] emphasize that significant changes in the hardening of steels occur only when the certain dose of irradiation is accumulated. It is noted in [20] that defects caused by irradiation act as hydrogen traps in austenitic stainless steels. It was shown that the irradiated steels showed a higher loss of viscosity and the presence of embrittlement in the presence of hydrogen.

R. Ricker and D. Pitchure [21] underline that during hydrogen embrittlement there is a slight, but statistically determined, decrease in the values of the modulus of elasticity in steels. The influence of hydrogen saturation on the physical and mechanical properties of austenitic steels 304 and 310S at normal temperature was studied in [22]. It is noted that with maximum hydrogen saturation of 310S steel, the modulus of elasticity can decrease by 10…11%, and for 304 steel - by 8…9%. J. Lee [2] introduced the HEE-index (Hydrogen Environmental Embrittlement – hydrogen-induced embrittlement of the material), which shows how the corresponding value of the physical and mechanical characteristics of the material changes when it is treated with hydrogen. Thus, for austenitic steels, this index is quite high, which shows a moderate effect of hydrogen addition. It is indicated that in steel 316 the elongation at break with a change in temperature from 0 to 100 °C varies within 0.7 to 0.8 of the value that occurs during tests in air. For steel 304L, this change is more significant – from 0.25 to 0.75.

So, the main conclusions that can be used in the statement of the boundary – initial value problems for RVI behaviour are reduced to the following: long-term hydrogen saturation reduces the modulus of elasticity of metallic materials; hydrogen embrittlement is concentrated in areas near the surface of the material; significant changes in the embrittlement of steels occur only when a certain dose of radiation is accumulated; the hydrogen diffusion process is strongly influenced by stress distributions and irreversible strains.

Next, if the problem of complex computational evaluation of long-term changes in the stress-strain state is formulated, it is necessary to use experimental data to formulate and further check the constitutive equations. Let us consider the recently developed implementations to the calculation methods using formulating special constitutive and evolution equations.

An effective approach to the formulation of constitutive equations for the Solid Mechanics problems using data from experiments on the analysis of the material structure during operation was proposed in [3, 4]. The influence of hydrogen on the kinematics, thermodynamics and kinetics of the evolution of irreversible strains and damage is obtained on the basis of the proposed Bammann continuum plasticity and Horstemeyer damage equations. In the latter, the failure criterion proposed by McClintock [23] due to the growth of pores is used. The results of nanoscale atomistic modelling and existing experimental observations were used. The proposed constitutive equations are implemented in Finite Element software. It is pointed out that the obtained numerical results showed a satisfactory agreement with the experimental data.

The study [5] presents an extension of the proposed model with constitutive equations for elastic-viscoplastic deformation under conditions of accumulated irradiation damage. The equations take into account strengthening by nuclear irradiation and varying of the brittleness of irradiated polycrystalline materials. Irradiation effects were added to the associated plasticity and damage kinetics by considering structure–property relationships. The current radiation-dependent elastic-viscoplastic-damage model was compared with experimental data for various metals, including modified 9Cr-1Mo steel. The results showed satisfactory agreement on all strain diagrams at different doses of irradiation.

Thus, implementation of the constitutive equations constructed with the use of qualitative and quantitative data from experimental studies at both the micro, meso, and macro levels makes it possible to conduct computational, primarily Finite Element modelling of irreversible deformation and accumulation of damage in the material of structural elements subjected by the combined influence of thermal, force and irradiation fields. The analysis of further possible failure is a complex task that is solved for certain important cases.

This paper contains an approach to the analysis of the long-term behaviour of elements made of 08X18N10T steel under the influence of irradiation and thermal stresses as well as damage accumulation due to radiation exposure and hydrogen embrittlement. The proposed constitutive and evolution equations were developed based on the ideas and results of [3–5].

PROBLEM STATEMENT

The mathematical problem formulation according to the previously formulated approaches [24–27] will be represented by a complete system of equations of the boundary-initial value problem. Let's consider the main features that allow us to formulate the problem statement. For it, as usual, differential equations of equilibrium and geometric relations are used. We limit ourselves to the case of small strains or small strains with finite displacements. We will use the fundamental hypothesis regarding the strains additivity [13] and take into account elastic, thermoelastic, irradiation creep and swelling strains. The components of the total strain tensor ε_{ij} are determined at each time moment as follows:

$$\varepsilon_{ij} = e_{ij} + e_{ij}^{T} + e_{ij}^{cr} + e_{ij}^{sw}, \tag{1}$$

where the following strain tensor components are presented: elastic e_{ij}; thermo-elastic e_{ij}^{T}; irradiation creep e_{ij}^{cr}; irradiation swelling e_{ij}^{sw}, $(i, j=1,2,3)$.

Thus, for a quasi-static loading of a structural element that is under the conditions of the joint action of thermal, force and irradiation fields, we write down the basic system of equations:

$$\sigma_{ij,j} + f_i = 0,\ \sigma_{ij} n_j = \tau_i,\ x_i \in S_2,$$
$$\varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i} + u_{k,i} u_{k,j}\right), \tag{2}$$
$$\sigma_{ij} = D_{ijkl}(e_{kl} - e_{kl}^{T} - e_{kl}^{cr} - e_{kl}^{sw}),\quad x_i \in V,$$
$$u_i|_{S_1} = \bar{u}_i,\ u_i(x,0) = e_{ij}^{cr}(x,0) = e_{ij}^{sw}(x,0) = 0,$$

where $\boldsymbol{\sigma}$ is the stress tensor; $\boldsymbol{u}$ is the vector of displacements; $\boldsymbol{n}$ is the normal unit vector on the surface S of the solid body with the volume V; $\boldsymbol{D}$ is the tensor of elastic properties; $\bar{\boldsymbol{u}}$ is the given displacement vector of the surface part S_1; $\boldsymbol{\tau}$ is the traction vector in the points of the surface part S_2.

To formulate the defining equation for the components of the strain rate tensor of irradiation swelling, we use the following dependencies:

$$\dot{e}_{ij}^{sw} = \frac{1}{3}\dot{S}_{\Phi}(D_a, t, T, \ldots)\delta_{ij}. \tag{3}$$

Function S_{Φ} [25, 26] depends upon accumulated dose D_a, time t, temperature T and experimentally determined parameters.

We write the additivity hypothesis for strain rates in the following form:

$$\dot{\varepsilon}_{ij} = \dot{e}_{ij} + \dot{e}_{ij}^{T} + \dot{e}_{ij}^{cr} + \dot{e}_{ij}^{sw}. \tag{4}$$

Thermal strains are taken into account in the classical way [13]:

$$e_{ij}^{T} = \alpha_{ij}(T - T_0)\delta_{ij}. \tag{5}$$

Here α_{ij} are coefficients of material thermal expansion.

To formulate the flow rule for the irradiation creep strain rate, we use Norton's classical power law [13]. We will use the most widespread and proven linear form of its dependence on stresses [14]:

$$\dot{\varepsilon}_{ij}^{cr} = \frac{3}{2} b_{cr} \sigma_{vM} s_{ij} \exp\left(-\frac{Q_c}{T}\right);\ Q_c = \frac{U_c}{R}, \tag{6}$$

where U_c is the value of activation energy of irradiation creep; R is the universal constant; σ_{vM} is the second invariant of stress deviator (von Mises equivalent stress); b_{cr} is the constant.

With long-term loading, there is an accumulation of hidden damage in the material, the action of which eventually leads to the appearance of a macroscopic defect (crack) or failure. The description of damage accumulation processes is carried out using the concepts of Continuum Damage Mechanics (CDM) [13]. At the same time, in the system of equations (1)–(6), the latter equation is replaced by Eq. (7), which considers the dependence of the strain rate on the scalar parameter of damage φ, and for this parameter itself, an evolution (kinetic) equation is formulated:

$$\dot{\varepsilon}_{ij}^{cr} = \frac{3}{2} b_{cr} \frac{\sigma_{vM}}{(1-\varphi)^k} \exp\left(-\frac{Q_c}{T}\right) s_{ij},\ Q_c = \frac{U_c}{R}. \tag{7}$$

EVOLUTION EQUATION FOR DAMAGE PAPAMETER

First, we will consider the approach to determining the effect of hydrogen embrittlement on the process of hidden damage accumulation. The main fact that can be used from the point of view of Solid Mechanics to analyze the long-term effect of hydrogen on the properties of the material is the decrease in the value of the modulus of elasticity.

What does this mean in terms of mechanics for tension behaviour? Consider the stress-strain diagram for isotropic homogeneous specimens with different modulus of elasticity E_1 and E_2 , $E_1 > E_2$. For these specimens, the same strain value will be reached during tension at different stress values, while, of course, $\sigma_1 > \sigma_2$ (Fig. 1).

How the same material in tension at different times (first, when deformed without considering the influence of the environment at the time t_0, and then under the long-term influence of this environment at the time t), will react differently to the same stress value σ_1, increasing the strain value from ε_0 to ε_1? This can happen only under the conditions of reducing the cross-section of the specimen. In the case under consideration, it can be under the conditions of reducing the effective cross-section of the specimen A, which perceives the external load – tensile force F:

$$\varepsilon_i = \frac{F}{A_i E},\ i=1,2,\ A_1 > A_2 \rightarrow \varepsilon_1 < \varepsilon_2 . \quad (8)$$

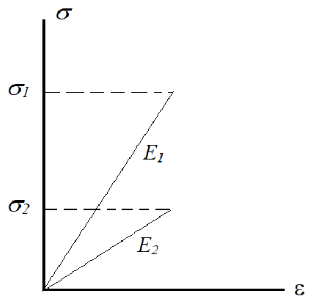

Fig. 1. Stress-strain diagram for specimens made from two materials

As is known [2, 15], hydrogen exposure leads to embrittlement of the surface layers of the material. In this regard, it is quite appropriate to assume that the mentioned decrease in the cross-section of the specimen occurs precisely due to the reduction/exhaustion of the load-bearing capacity on the outer fibers of the material.

Let us express the current value of the modulus of elasticity E in terms of its initial value E_0, which corresponds to the state of the material with the absence of hydrogen exposure:

$$E = E_0(1-h),\ 0<h<1 , \quad (9)$$

where h characterizes the decreasing of the material modulus of elasticity, theoretically $0<h<1$. Let us write down the expression for the current value of the strain at any time t:

$$\varepsilon = \frac{F}{AE_0(1-h)} . \quad (10)$$

Then, having the value of the decrease of the modulus of elasticity with time, it is possible to introduce the function of the decrease of the cross section of the specimen $f(A)=A(1-h)$ dependent on it, formally transferring the term to the value of the area A and considering that the current value of the stress is

$$\sigma = \frac{F}{A_0(1-h)} . \quad (11)$$

This provides an opportunity to proceed to the use of the main CDM hypothesis regarding the effect of the effective stress on the long-term strength of the material during its damage accumulation over time [13]:

$$\sigma = \frac{F}{A_0(1-h)} = \frac{\sigma_0}{1-h}, \sigma_0 = \frac{F}{A_0} . \quad (12)$$

Next, it is necessary to formulate the evolution equation for the hydrogen embrittlement parameter h. We will build it using, firstly, experimental data on the reduction of the modulus of elasticity of the material under conditions of long-term hydrogen embrittlement, and, secondly, assumptions on the mathematical form of the dependence of the parameter h on time. It is clear that for the construction of the evolution equation, which is written for the rate of varying of the corresponding variable, in this case the parameter h, the linear form is inadmissible (the derivative will take a zero value). It is also not good to obtain a linear dependence in the evolution equation, it does not correspond to qualitative observational data on the nonlinearity of the effect of embrittlement with time. That is, the quadratic dependence is also not suitable. In this regard, we use the minimum cubic form of the dependence of the parameter h on time. As is accepted in CDM [13]:

$$t=0:\ h=0, \qquad t=t_f:\ h=h_{max} . \quad (13)$$

Here t_f is the time value of the embrittlement process; h_{max} is the maximum value of the parameter h; which achieves in experiments after the time t_f. Let us write down the form of the function proposed for the dependence of the hydrogen embrittlement parameter on time:

$$h = C_f t^{p+1}, p \geq 3 . \quad (14)$$

Here C_f, p are the constants which determine experimentally for considered temperature range. By differentiating, we get the form for the evolution equation:

$$\dot{h} = C_f(p+1)t^p = Ct^p, C = C_f(p+1). \quad (15)$$

It is clear that this equation will be valid only for areas of the material that are close to its surfaces, where hydrogen embrittlement occurs.

We will obtain the value of the constant C_f, which is included in the evolution equation for the parameter h. Let's use the initial conditions (13). We get:

$$C_f = \frac{h_{max}}{t_f^{p+1}} . \quad (16)$$

By use of p= 3, h_{max}=0.1 for the steel of 304 type [22], t_f=30 years = 26,2800 h, we have: C_f = 2.64 $10^{-21}\cdot(\mathrm{h})^{-(p+1)}$.

To describe the damage accumulation in the material as a result of the influence of temperature-force and irradiation fields, we will use an equation built on the basis of the model of Horstemeyer and co-authors [3], [4]. The main idea of the evolution equation developed by them for the scalar damage parameter φ is that the damage accumulation function in the case of temperature-force and radiation fields in steels is dependent on two main processes – the nucleation of pores η and the growth of pores *v,* which affect each other one. Damage accumulation rate is defined as

$$\frac{d\varphi}{dt} = \frac{d(\eta v)}{dt} . \qquad (17)$$

For the mathematical representation of the spherical pore growth function *v*, the authors of [4] used the model [23], in which *v* depends on the exponential dependence of the irreversible strain function (the second invariant of the strain tensor under a complex stress state). The influence of the ratio of the second invariant of the stress tensor I_2 on the second invariant of the deviator of the stress tensor J_2 is considered.

The formulation of the pore nucleation function η was performed in [4] using the information of its exponential dependence on the level of irreversible strains. In turn, under the exponent there is also an exponential dependence on the concentration of hydrogen, which characterizes the embrittlement of the material. The authors take into account the possibility of unequal response to different types of load, and also use the ratio of the first and third invariant of the stress tensor to the second invariant of the deviator of the stress tensor. The authors use the value of the fracture toughness of the material as one of many coefficients. Among other coefficients, values of the average initial pore radius, volume concentration of particles, scale parameter, etc. are used. It is quite clear that such functions can be built only if the results of full-scale experimental studies are available. The data obtained for one of the steels are used in [4].

Analysis of the proposed functions included in the evolution equation for the damage parameter (17) shows that from the point of view of the CDM [13] it is an equation whose coefficients affect the values characterizing the representative volume element (RVE [13]). These values are the components and invariants of stress and strain tensors. It can be considered as constructed using phenomenological approaches, and the unknown constants as obtained from mechanical studies of long-term deformation and fracture of the material (long-term strength).

Let us use this conclusion to construct the evolution equation for the damage parameter for steel type 08X18N10T. We apply the main functional dependencies defined in [4]. Due to the lack of data on the influence of the type of stress state on the process of damage accumulation, we limit ourselves, as in the classical approaches of Solid Mechanics [13], only to the influence of the stress state during tension.

First, we consider the formulation of the expression for the growth rate of spherical pores *v*. As is known, this process determines the accumulation of hidden damage during creep [13]. To describe it, a scalar damage parameter is used, which is determined by a differential equation of the first order. For the damage parameter *v*:

$$\frac{dv}{dt} = C_v \frac{\sigma^n_{vM}}{(1-v)^n}, v(0) = 0, v(t_*) = 1. \qquad (18)$$

Here C_v, *n* are the material parameters or functions, which determine experimentally for considered temperature range [13]; t_* is the value of the time to finish the hidden damage accumulation; σ_e is equivalent stress, which determines due to long term strength criteria for considered temperature range [13]. To clarify the form of the C_v function, we will use the results obtained during the formulation of the evolution equation in [4]. We assume that C_v depends on the rate of the second invariant of the tensor of irreversible strains (von Mises equivalent strain). In the case under consideration, this strain is a sum of irradiation creep strain and, from a certain time moment, of the irradiation swelling strain. The value of the von Mises strain affects the course of the process of accumulation of hidden damage exponentially. At the same time, as in [4], we consider the influence of the average stress (the first invariant of the stress tensor I_1), relating it to the second invariant of the stress tensor deviator J_2. The course of the real process of damage accumulation due to the growth of pores will be reflected by entering the material constants *D*, *n* and *G*. Taking into account the described dependencies, the evolution equation (18) will take the following form:

$$\frac{dv}{dt} = D\frac{\sigma^n_{vM}}{(1-v)^n} \dot{\varepsilon}^i_{vM} \exp\left(G\varepsilon^i_{vM} \left| \frac{I_1}{J_2} \right| \right), \qquad (19)$$

$$v(0) = 0, v(t_*) = 1.$$

Next, let us consider the mathematical representation for the pore nucleation function η. As in [4], this function will reflect the effect of hydrogen embrittlement with the current strain level, which will also be presented in an exponential form. As one of the coefficients, according to [4], we will use the value inverse of the steel fracture toughness of K_{1C}. Let us take the pore nucleation function η in the following form:

$$\eta = \exp\left(\frac{\varepsilon^i_{vM}}{K_{1C}} C_f t^{p+1} \right), \eta(0) = 0. \qquad (20)$$

Now it is possible to obtain the form of the general evolution equation (17) for the damage parameter φ. We will assume that the pore nucleation rate is quite small, close to zero. Then Eq. (17) will take the following form:

$$\frac{d\varphi}{dt} = \eta\frac{dv}{dt} = \exp\left(\frac{\varepsilon^i_{vM}}{K_{1C}} C_f t^{p+1} \right) D\frac{\sigma^n_{vM}}{(1-\varphi)^n} \dot{\varepsilon}^i_{vM} \exp\left(G\varepsilon^i_{vM} \left| \frac{I_1}{J_2} \right| \right),$$

$$\varphi(0) = 0, \varphi(t_*) = 1. \qquad (21)$$

The components of irreversible strain tensor ε^i_{ij} in considered case consist from the sum of the irradiation creep and swelling strain tensor components:

$$\varepsilon^i_{ij} = \varepsilon^{cr}_{ij} + \varepsilon^{sw}_{ij} . \qquad (22)$$

For the description of irradiation creep in considered conditions we use the constant b_{cr} = 1.21410^{-12} MPa^{-1}/h [26].

As is known [12], significant growth of irradiation swelling strains begins only after a sufficiently long time of operation t_s. Let us consider the description of irradiation swelling strains. The swelling function in steel of type 08X18N10T has a complex dependence on temperature T [12]. But in the considered range, from 573 to 710 K, it can be approximated by a linear dependence in the first approximation:

$$\dot{\varepsilon}^{sw}_{vM} = \dot{\varepsilon}^{sw710K}_{vM}\left(0.0058T - 3.145\right), \qquad (23)$$

where $\dot{\varepsilon}^{sw710K}_{vM}$ is irradiation swelling strain rate at T=710 K and value of the dose rate k=5.4·10^{-8} dpa/s and $t>t_s$.

From the CDM point of view, the form of Eq. (21) differs from the classical equation for a scalar damage parameter of the type, for example (18), in that the damage accumulation rate is affected not only by the current stress level, but also by the strain level considering the type of stress state. The deformed state affects indirectly, through the influence of hydrogen embrittlement and the type of stress state. The analysis of Eq. (21) also shows that it contains a reflection of the influence of the power (the product of the rates of von Mises strains and stresses).

One of the most important stages of preparation for numerical modeling is the determination of the constants included in the proposed evolution equation. Similar to the traditional approach [13], we write equation (21) for the case of a uniaxial stress state with irreversible strain ε^i and stress σ:

$$\frac{d\varphi}{dt} = \exp\left(\frac{\varepsilon^i}{K_{1C}} C_f t^{p+1}\right) D \frac{\sigma^n}{(1-\varphi)^n} \varepsilon^i \exp\left(G\varepsilon^i\right), \qquad (24)$$

$$\varphi(0) = 0, \varphi(t_*) = 1.$$

In this equation we have unknown constants D, n, and G. At first stage we consider only the irradiation creep process and $\varphi=\varphi^r$:

$$\dot{\varphi}^r = D\frac{\sigma^n}{(1-\varphi^r)^n}, \varphi^r(0) = 0, \varphi^r(t_*) = 1.$$

Using the technology of determining the constants from the long-term strength curve, the data on the failure at a stress of 385 MPa for 10,000 h [9] and at low stresses over a fairly long period of time (>80 years), we determine the values of the constants: n=2.3, D = 6·10^{-7}(MPa)$^{-n}$/h.

In order to determine the value of constant G we use the condition $\varphi(t_*) = 1$. Let us integrate the equation (24). We obtain:

$$\varphi = 1 - \left(-(n+1)\sigma^n D\int_o^t \exp\left(\frac{\varepsilon^i}{K_{1C}} C_f t^{p+1}\right)\varepsilon^i \exp\left(G\varepsilon^i\right)dt\right)^{\frac{1}{n+1}}. \qquad (25)$$

In the moment of the finishing the hidden damage accumulation $\varphi(t_*) = 1$. Set $t=t_*$, $\varepsilon^i=\varepsilon^i_*$ we have:

$$1 = 1 - \left(-(n+1)\sigma^n D\exp\left(\frac{\varepsilon^i}{K_{1C}} C_f t_*^{p+1}\right)\dot{\varepsilon}^i_*\int_0^{t_*} \exp\left(G\varepsilon^i_*\right)dt\right)^{\frac{1}{n+1}}. \qquad (26)$$

From Eq. (26), we obtain the value of the constant G. To use this approach, it is necessary to know the values included in (26). Analyzing results presented in [2] and [9], we will assume σ=460 MPa (the maximum stress value in the reactor baffle), t_*=31 h, ε^i_* =2.4%. K_{1C}=45 MPa$\sqrt{m}$ [28]. For these values of parameters, the value G=3·10^{-20} is obtained.

ANALYSIS OF NUMERICAL DATA

The *FEM Creep* software complex with additional modules of the *FEM Creep Damage Fracture* program [29] was used to assess the deformed state and the level of hidden damage. In this software the numerical simulation under a two-dimensional stress state is performed using the FEM and differential time integration methods. The main components of the method with the features of its application to elements of nuclear reactors are described in [25, 26]. In this paper, additionally developed software modules were used for the implementation of the evolution equation and for determining the sets of finite elements that are situated near the surface of the structural element in order to assign them additional properties of accumulation the hidden damage levels due to hydrogen embrittlement.

Let's analyze the results that can be obtained when using the evolution equation (21). First, let's analyze equation (24) for a uniaxial stress state.

Let us consider a long rod in which a 1D stress state is realized. The tensile stress is 460 MPa, this value is the maximum possible at the thermal-force loading of the reactor baffle of the WWER-1000 type [25]. The rod is heated to a temperature of 710 K. It is in the conditions of radiation exposure described above. The time of the beginning of the significant influence of irradiation swelling strains is chosen to be t_s=200,000 h. Until that moment, only irradiation creep strains contribute to the total irreversible strain level. Due to the peculiarity of the 1D calculation scheme, it is assumed that hydrogen embrittlement occurs at all points of the rod. This will definitely lead to an evaluation of the damage accumulation process as overestimated.

The results of the numerical integration of Eq. (24) are given in the Fig. 2. Here, curve 1 corresponds to the result obtained for the complete form of Eq. (24), i.e., considering hydrogen embrittlement. Curve 2 is built without taking into account the pore nucleation function η. The analysis of the results shows that with the onset of a significant effect of radiation swelling, the radiation damage parameter φ begins to increase. If all the factors of Eq. (24) are fully considered, the hidden damage accumulation is completed after 274,000 h, which roughly corresponds to 31.3 years. In the case where hydrogen embrittlement is not taken into account, a low rate of damage accumulation is obtained, in which in 520,000 h, which corresponds to approximately 60 years of operation, the hidden fracture is not completed, and the damage parameter reaches a value of 0.06.

Now let's move on to the analysis of the problem, which can be considered as intermediate. It will use the full formulation for the case of a complex stress state, but the scheme will correspond to uniaxial tension. Such a task is necessary for a complete verification of the calculation method using the proposed evolution equation (21).

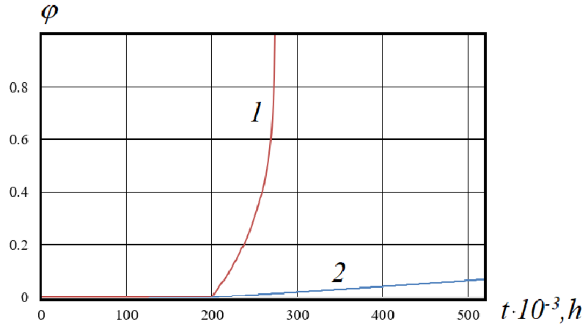

Fig. 2. The damage parameter versus time. Uniaxial tension, 1D case. Curve 1: consideration of hydrogen embrittlement. Curve 2: without consideration

Let us consider a plate of 100x20 mm, 1 mm thick, fixed on the smaller side. On the opposite side, the traction p = 450 MPa is applied.

After numerical experiments, a finite element mesh of 4000 elements was adopted for modeling. Calculations of the initial stress state showed an almost uniform stress distribution.

First, as in the previous example of the analysis of a 1D equation, we will assume that Eq. (21) is valid for all points of the plate, that is, the processes of damage growth and embrittlement proceed in them in the same way. This corresponds to the case of access of the influence of the hydrogen embrittlement process to all surfaces of the considered thin plate.

The distribution of the irreversible von Mises strains for the moment of completion of hidden damage accumulation 324,928 h (37 years) is presented in Fig. 3. The resulting strain distribution shows their localization with a level of 2.4% in the fixed area, where the greatest initial stresses occur. It can be assumed that due to the strain compatibility, the irradiation swelling components develop a little slower near the fixed area than in the rest of the plate volume. In the main areas of the plate, there is a rather significant strain level of 1.7…1.9%.

Fig. 3. Distribution of the of irreversible von Mises strains along the plate at t=324,928 h

The analysis of the obtained results shows that the process of completion of hidden damage accumulation occurs in the fixed area. Due to the fact that in the conditions of the problem it was specified that the embrittlement spreads over the entire area of the plate, the average level of damage in the plate it acquired as significant and reaches 0.19. (In classical creep problems, damage is localized in the area of maximum stresses, and in the rest of the material it does not exceed 0.05…0.01). The obtained location of failure and the distribution of the damage parameter along the plate indicate that the use of the calculation method and the proposed evolution equation provides quite plausible results.

Further, in the calculation scheme, it was assumed that only the lateral layers of finite elements are characterized by the presence of hydrogen embrittlement. This corresponds to observational data indicating its predominant concentration on surfaces. In this formulation, we assume that the main surface of the plate is isolated and it is not affected by hydrogen embrittlement. It is clear that this is a model problem, which is necessary for further investigation of the behavior of structural elements in which plane strain conditions are realized.

The results of solving this problem are shown in Figs. 4 and 5. Fig. 4 contains the distribution of the damage parameter for the plate at the time of 417,415 h (47.6 years). Hidden damage, as in the previous case, first occurs in the fixed area, but the acquired level of damage at the edges is significant and reaches from 0.37 to 0.49. The inner area of the plate is slightly damaged.

Fig. 4. Distribution of the damage parameter by plate at t=417,415 h

Further, with the help of algorithms for taking into account the fracture processes by excluding "destroyed" finite elements [29], in which the damage parameter reaches its critical value (0.95…0.98 due to the peculiarities of the numerical solution process), the process of further damage development in the plate was simulated. Starting from the moment t=453,486 h, the rapid termination of joint development of embrittlement processes and accumulation of irradiation damage begins due to failure in plate sides. The elements of the outer layers of the plate “destroy”, where high values of the damage parameter were reached. The configuration of the plate achieved at t = 454,651 h is presented in Fig. 5.

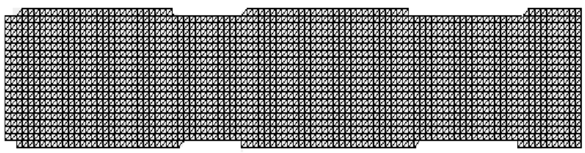

Fig. 5. The current configuration of the plate under the conditions of the development of the fracture process at t= 454,651 h

From the analysis of the model presented in Fig. 5, it can be seen that the calculation scheme used provides a completely physical representation of the processes of degradation and fracture of the material as a result of the joint action of hydrogen embrittlement and radiation exposure.

Now after testing it is possible to proceed to the analysis of the influence of the stress-strain state in the vicinity of the cooling holes that exist in the baffle of the WWER-1000 type reactor. For this, we will consider a simplified calculation scheme of a long tube with a through hole, in which the diameters of the tube and the hole are close to the real ones in the baffle. Such a scheme is necessary for a detailed study of the behavior in the vicinity of one hole. The obtained conclusions can be transferred to the case of a real design. As a calculation scheme, we consider a tube section with an outer radius of 1.76 m and an inner radius of 1.6 m. The radius of the hole is 0.025 m. It is assumed that is on the inner surface of the hole the temperature value is 300 °C. In the tube, a temperature distribution that is stationary in time and uneven in radius with a logarithmic law, is implemented, which corresponds to the boundary conditions at the inner radius of T=410 °C and at the outer radius of 300 °C. It was assumed that the material of the tube is irradiated and irradiation creep and swelling strains develop in it. The time of the beginning of the significant influence of irradiation swelling is chosen to be t_s=200,000 h. It was assumed that the material on the tube surfaces was exposed to hydrogen embrittlement.

The problem is solved using the plane strain formulation. Due to symmetry, one fourth of the cross section is considered. On the surfaces of the tube, we set two layers of finite elements, in which the properties of hidden damage accumulation include consideration of hydrogen embrittlement. The same four layers of elements are set on the inner surface of the hole. Their larger number is determined by the size of the elements when the finite element mesh is thickened in the vicinity of the hole. After studies of the convergence of numerical solutions, a model with 3513 nodes and 6558 finite elements was selected (Fig. 6).

After solving the stationary heat problem, the solution of the problem of thermo-elasticity in tube [30] was obtained. For it in Fig. 7 the distribution of von Mises equivalent stresses is presented.

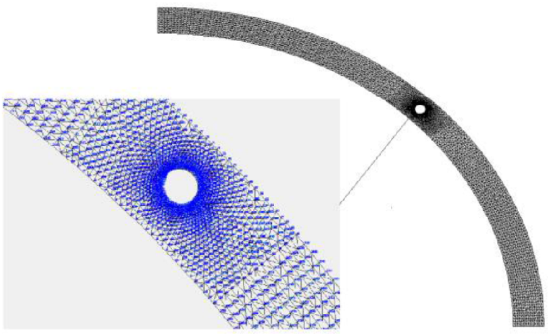

Fig. 6. Finite element model for a tube fragment with a hole

It can be seen from Fig. 7 that at a distance from the hole there is a typical stress distribution in the tube with the used logarithmic law of temperature dependence on radius. At the same time, the presence of temperature differences in the vicinity of the hole creates an additional stress concentration there with levels corresponding to the maximum values on the tube surfaces.

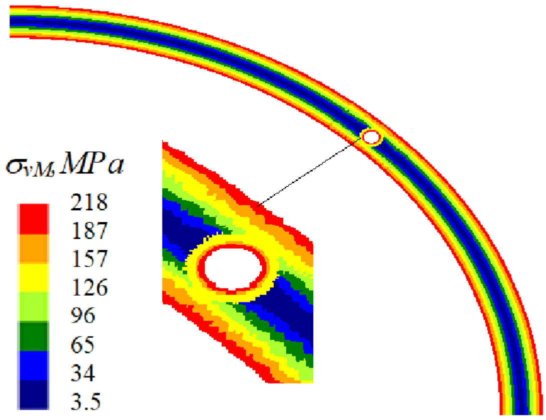

Fig. 7. Distribution of von Mises equivalent stresses through the tube cross section at t=0 h

Let us present the results of numerical modeling of deformation accompanied by the accumulation of hidden damage due to radiation exposure and hydrogen embrittlement. For the described conditions, the calculated time until the completion of hidden damage accumulation was 258,000 h. The calculation results for this moment are shown in Fig. 8 (distribution of von Mises equivalent strains across the cross-section) and Fig. 9 (damage parameter).

As can be seen from the distributions shown in Figs. 8 and 9, the maximum values of strains and damage parameter are at the inner radius, which corresponds to known solutions (see, for example, [25]). At the same time, there are fluctuations around the hole. Despite the fact that hidden damage accumulation, as in the previous case, ends at the points of the inner radius – at the point opposite the opening (see Fig. 9), zones with a significant level of damage (see 0.2–0.3, Fig. 9) appear in its vicinity, localized in the direction of the inner radius. Judging by the rather fast, non-linear rate of growth of the damage parameter in the given range of its values, fracture in the vicinity of the hole may occur within the next hundreds of hours. A slight increase in the strain level around the hole is explained by the fact that the main contribution to this process is provided by irradiation swelling, the rate of which is significantly dependent on temperature. The temperature around the hole is lower than at the corresponding radius of the tube.

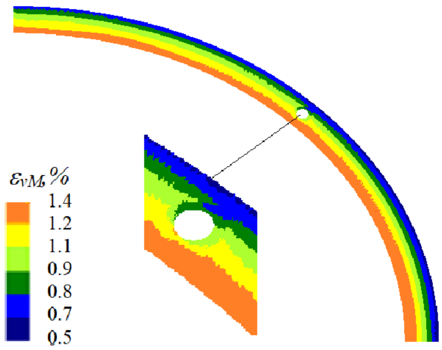

Fig. 8. Distribution of von Mises equivalent strains through the tube cross section at t=258,000 h

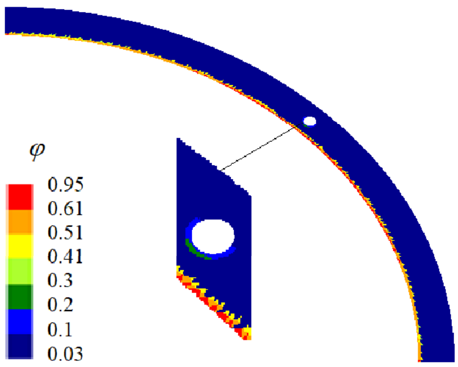

Fig. 9. Distribution of the damage parameter through the tube cross section at t=258,000 h

In order to demonstrate the main role of the temperature distribution around the hole on further deformation and hidden damage accumulation, consider the second example. The only difference between it and the first one will be the lack of coolant temperature on the surface of the hole. This, accordingly, will lead to the absence of an additional stress drop there. Fig. 10 shows the distribution of the damage parameter around the hole. It can be seen that there is no high level of damage. Therefore, the main contribution to the process of its accumulation in this case is determined by the balance of temperature and stress levels. The temperature stress distribution is determined by the temperature difference. When its level increases, the stress level will be approximately the same, and the rate of irradiation swelling will increase. That is, at a high temperature on the surface of the hole, damage will accumulate much faster. Fortunately, this is a hypothetical case.

In the next, third example, we will keep all the conditions specified for the first one, but we will assume that the radiation dose rate is k=2.57·10^{-8} dpa/s, that is, it is reduced by two times. The results of the calculations showed that the time until the completion of hidden damage accumulation increases by 1.3 times, up to 333,700 h (38 years). The distribution of the values of the damage parameter by the tube cross-section, comparing with the first example (see Fig. 9), does not change qualitatively and practically quantitatively. But such a pattern of distribution is obtained over a longer time. Strains grow more slowly, the maximum von Mises equivalent strain does not exceed 1%. Strain distribution qualitatively corresponds to that shown in Fig. 8.

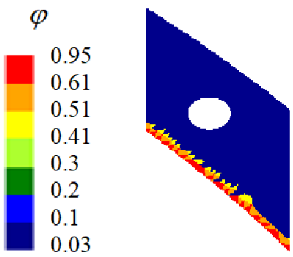

Fig. 10. Distribution of the damage parameter around the hole. The temperature on the surface coincides with the temperature at the corresponding tube radii at t=258,000 h

In the fourth example, we will consider the problem with the conditions of the first example, but we will apply the hyperbolic dependence of the dose accumulation on the radius proposed in [25], [26]. The value of the completion time of the hidden damage accumulation process was obtained by calculations. It was 283,000 h (32.3 years). The distribution of values of the damage parameter according to the tube cross-section is given in Fig. 11. Comparing it with those obtained for other options, we see the absence of significant damage around the hole. The main damage, as well as the location of the macroscopic defect, is localized on the inner surface of the tube, as was obtained in the previous examples. The lack of significant damage around the hole is apparently due to the lower rate of dose accumulation. The strains in this problem grow similarly to that which were established in the first example, the maximum value of the von Mises equivalent strain is 1.4%. This is due to the fact that the value of the maximum rate of dose accumulation remained unchanged in the regions of the inner surface, where the maximum strains take place. The obtained distribution of the von Mises strains corresponds to that shown in Fig. 9.

CONCLUSIONS

The use of the developed evolution equation for the damage parameter, which was added to the previously proven method and software for modeling structural elements exposed to thermal, force and irradiation fields, showed the possibility of practical assessment of the deformed state and the level of accumulated hidden damage.

The paper proposes and uses an approach that allows you to use the qualitative results of formulating the so-called "mechanism based" evolution equations, i.e. constructed using experiments at the micro- and meso-level, to determine the structure of the evolution equation for another, similar in composition, material. This approach was used due to the lack of experimental data on the long-term damage accumulation in the considered steel 08X18N9T under the given conditions of temperature and radiation exposure. The basic mathematical nature of the effects of various processes on the course of hidden damage accumulation, established in [3, 4], was used to reproduce it in the proposed equation. Similarly, consideration of the influence of the type of stress state due to tensor and stress deviator invariants has also been added. The effect of hydrogen embrittlement is realized through the known data of experiments performed at the macro level: changes in the modulus of elasticity are taken into account. The function actually obtained in this case entered in the evolution equation in an exponential form, as obtained in [3, 4]. To determine damage due to irradiation influence, the classical approach of CDM was used [13].

When determining the values of constants included in the evolution equation, several assumptions were used, the main of which is information about the time of completion of hidden damage accumulation in one-dimensional specimen under the considered conditions and the presence of deformation due to irradiation creep, irradiation swelling, hydrogen embrittlement, etc. These data were approximately taken from [3, 25] with a safety factor of 1.25. In addition, one of the values on the long-term strength curve of the considered steel was approximated.

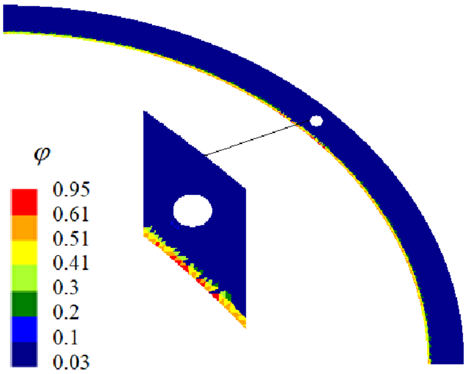

Fig. 11. Distribution of the damage parameter through the tube cross-section. Dependence of the dose accumulation rate on the radius at t=283,300 h

The main task of the construction of the evolution damage equation was to demonstrate the possibility of its application in the calculation analysis under a complex stress state, which is realized in the RVI structural elements, for the analysis of various operating conditions with the determination of the probable time until the completion of hidden damage accumulation with the arising of macroscopic defects. Such an equation can be constructed using operating data with the involvement of witness specimens from reactors. At the same time, thanks to Materials Science research, quantitative and qualitative laws of the processes of nucleation and growth of pores can be established, which will provide opportunities for clarification when formulating the evolution equation for steel type 08X18N9T in the temperature and radiation ranges corresponding to the operating conditions of the WWER-1000 type reactor.

The main conclusions obtained during computer modeling can be summarized as follows.

The obtained numerical results showed that the main contribution to the processes of accumulation of hidden damage is made by the processes of irradiation swelling in conjunction with hydrogen embrittlement. The interaction of processes is essentially non-linear. On the surfaces of the elements, where the maximum values of the dose accumulation rate are present, hydrogen embrittlement processes significantly intensify the damage accumulation rate. This is due to the growth of stress components caused by increased strains of irradiation swelling. Due to the nonlinearity of the processes, smaller stress values do not lead to large values of the damage parameter.

The presence of a close level of accumulated damage on the inner radius of the tube is explained by the use of a simplified model. By use of the numerical model of the real baffle cross-section, as it was shown in [25, 26], there are different values of stresses on the inner surface of a complex shape. Due to the concentration of stresses in the baffle, the location of the macroscopic defect is localized. In this work, the main attention was paid to the analysis of the behavior of deformation and hidden damage accumulation between holes and surfaces, taking into account hydrogen embrittlement of the surface of the hole. For this purpose, a computational was built with the mesh concentration in the vicinity of the hole. The obtained results showed that the dependence of hydrogen embrittlement in the vicinity of the hole is not critical for the general assessment of damage, which means that it is possible to perform the calculations of the baffle model with the computational models made in [25, 26].

Taking into account the radial dependence of the rate of dose accumulation in the calculations does not lead to qualitative changes in the obtained distributions, and the values of the time until the completion of hidden damage accumulation differ slightly, by a factor of 1.09. The main point in the difference between the results is the presence of a fairly significant level of damage in the vicinity of the hole, which is leveled off in the more realistic model of the radial dependence of radiation swelling.

Therefore, it is possible to propose a simplified method for the analysis of the long-term behavior of similar RVI structural elements. It is necessary to solve the thermoelastic problem and determine the places with the highest stress level. Determine the surfaces with the maximum level of dose accumulation rate and temperature level. It is on these surfaces that the hidden damage accumulation is likely to finish with an arising of macroscopic defect. The time to failure can be approximately estimated by the integration of the evolution equation for the maximum value of the equivalent stress, which is determined from experimental data by a combination of the invariants of the stress tensor (the most common case is the use of the second invariant, the von Mises equivalent stress) and the maximum temperature value.

Such a simplified method must be verified in the future when models of RVI structural elements with calculation schemes as close as possible to real ones.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ НАКОПИЧЕННЯ ПРИХОВАНИХ ПОШКОДЖЕНЬ ВНАСЛІДОК РАДІАЦІЙНОГО ОПРОМІНЮВАННЯ ТА ВОДНЕВОГО ОКРИХЧЕННЯ

Дмитро Бреславський, Оксана Татарінова, Галина Толстолуцька, Хольм Альтенбах

Запропоновано підхід, який дозволяє використовувати якісні результати аналізу так званих «physical based» еволюційних рівнянь, тобто побудованих за допомогою використання експериментів на мікро- та мезорівні, для визначення структури еволюційного рівняння для іншого, близького за складом, матеріалу. Для визначення пошкоджуваності внаслідок радіаційних пошкоджень використано класичний метод континуальної механіки пошкоджуваності. Запропонований підхід якісного відтворення ефектів накопичення пошкоджень використано за браком експериментальних даних щодо довготривалої поведінки матеріалу, що розглядається (сталі 08Х18Н9Т), при заданих умовах температурного та радіаційного впливів. Раніш вивчений характер впливів різних процесів на перебіг накопичення прихованих пошкоджень використано для його відтворення у запропонованому рівнянні. Враховано вплив типу напруженого стану через інваріанти тензора та девіатора напружень. Вплив водневого окрихчення відбито із застосуванням відомих даних експериментів, виконаних на макрорівні, враховано змінювання модуля пружності. Отримана при цьому функція ввійшла до еволюційного рівняння в експоненційному вигляді. Розроблене еволюційне рівняння для параметра пошкоджуваності додано до раніше перевіреного методу та програмного забезпечення для моделювання елементів конструкцій, що піддані дії термосилових та радіаційних полів. Надано приклади аналізу задач деформування й руйнування зразків та труби з наскрізним отвором, у якій моделюється поведінка відповідних зон вигородки реактора. Проведені чисельні розрахунки показали можливість практичного оцінювання деформованого стану та рівня набутих прихованих пошкоджень.