WELDED STRUCTURES FROM AUSTENITIC STEEL OF 10Kh18N10T TYPE UNDER CONDITIONS OF RADIATION-INDUCED SWELLING

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Mathematical modeling of deformation processes in different structural elements from steel 10Kh18N10T under radiation-induced swelling conditions showed peculiarities of their behaviour, allowing for residual welding stresses depending on the radiation dose, temperature and external load.

Keywords: *radiation-induced swelling of material, radiation dose, radiation creep, residual stresses*

Austenitic steels of 10Kh18N10T type are characterized by high levels of corrosion crack resistance, cold resistance, are readily weldable, and have high ductile properties, that promotes their wide application in critical structures, also in the field of nuclear engineering, where this steel is the main material of the so-called reactor internals (RI) operating at high radiation exposure doses. Such steels have high physico-mechanical properties, stable structure right up to temperatures of about 800 °C.

The above-mentioned stabilization is not absolutely invulnerable. In particular, long-term heating of austenitic steel in the temperature range of approximately 500–900 °C promotes the so-called $\gamma \to \alpha$ (austenitic-ferritic) transformation with concurrent formation of carbides, intermetallics, etc., leading to a quite abrupt change of steel properties, particularly in aggressive media, and to brittle fracture susceptibility. Temperature conditions of welding heating can to a certain extent cause sensibilization (increased susceptibility) of austenitic steel to corrosion and brittle fractures [1]. A similar factor lowering stability of austenitic microstructure is irradiation of structural elements from austenitic steel that is extremely typical for RI of modern nuclear reactors [2, 3].

In terms of engineering of RI elements, irradiation changes the mechanical and physical properties of materials of RI elements and hence the hazard of violation of integrity of these elements operating under extreme conditions, that determines the safety of operation of nuclear engineering facilities in many countries, including Ukraine. At present sufficiently reliable data are available as regards the change of mechanical properties of austenitic steels at irradiation. Long-term exposure of these steels involves the physical phenomenon of austenitic steel swelling (an irreversible process of volume increase) that may lead to an essential change of stressed state in structural elements with the respective consequences. It should be kept in mind that the swelling process largely depends not only on the radiation exposure, but also on temperature of material irradiation and non-linearity of stresses and plastic strains associated with material swelling.

Proceeding from experimental studies [4–8] of the respective samples from austenitic steel, it was established that the relative change of volume V at radiation exposure can be presented as

$$S = \frac{\Delta V}{V} = C_D D^n f_1(T) f_2(\sigma) f_3(\omega_p), \tag{1}$$

where $C_D = 1.035\cdot 10^{-4}$ dpa$^{-1.88}$ (dpa dimension — displacement per atom); D is the dose of irradiation with not more than 0.5 MeV energy; $n = 1.88$ according to [3]; $f_1(T)$ is the correction for material temperature T; $f_2(\sigma)$ is the correction related to the volume invariant of stress tensor. The following dependence is used at irradiation [9]:

$$f_1(T) = \exp\,[-(T - T_{max})^2 r], \tag{2}$$

where T_{max} is the peak irradiation temperature equal to about 470 °C [6]; $r = 1.1\cdot 10^{-4}$ °C^{-2} [9] is the experimental constant;

$$\sigma = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{3};$$

σ_{xx}, σ_{yy}, σ_{zz} are the normal components of stress tensor of irradiated material;

$$f_2(\sigma) = 1 + p\sigma \text{ at } 1 + p\sigma \ge 0, \quad f_2(\sigma) = 0 \text{ at } 1 + p\sigma < 0; \tag{3}$$

p is the experimental quantity having the value of approximately $4\cdot 10^{-3}$ 1/MPa^3; $f_3(\omega_p)$ is the correction for the level of plastic strains related to tensor invariant ε_{ij}^p by Odqvist strain hardening parameter

$$\omega_p = \int_0^D d\varepsilon_i^p, \tag{4}$$

where

$$d\varepsilon_i^p = \frac{\sqrt{2}}{3}\sqrt{d\varepsilon_{ij}^p d\varepsilon_{ij}^p} \quad (i, j = x, y, z)$$

is the intensity of plastic strain increment.

The dependence

$$f_3(\omega_p) = \exp(-\eta\omega_p) \qquad (5)$$

is used, where $\eta = 8.75$ for the considered steels [3].

From dependencies (1)–(5) it is seen that swelling level S rather strongly depends on damaging dose of radiation with more than 0.5 MeV energy, on absolute value of temperature difference $|T - T_{max}|$ of irradiated material, value and sign of spherical stress tensor

$$\delta_{ij}\sigma = \begin{vmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & \sigma \end{vmatrix},$$

and plastic strain accumulation parameter ω_p.

In terms of ensuring the integrity of RI elements it is important to determine how the swelling process, related to accumulation of dose D in operation, interacts with initial temperature stresses at reactor commissioning or with residual technological (for instance, welding) stresses. It is obvious that at uniform swelling $S(x, y, z)$ = const of a specific RI element, similar to uniform heating $T(x, y, z)$ = const, no stresses develop (except for reactive stresses, related to element fastening).

In [7, 8] it is shown that the process of material swelling is accompanied by lowering of the initial stressed state, as at respective temperature annealing, when reversible elastic strains go to irreversible strains of diffusion ductility through the mechanism of material creep. The term of «radiation creep» [7–9] is associated with this phenomenon. It should be noted that irradiation of a solid does not change the main regularities of deformations of continuum mechanics in terms of the phenomenological approach, except for mechanical properties of the deformed solid, determining the kind of deformation, namely elastic, instant plasticity, diffusion plasticity (creep). In this connection (as long as there are no additional kinds of deformation in the mechanics of solid deformation), the relationships of strains and stresses change qualitatively and quantitatively, their parameters being determined experimentally on the respective samples, depending on the specific conditions and material.

Considering a rather high interest to application of calculated predictions of RI element performance in modern nuclear reactors of WWER-1000 type and certain doubts as to the reality of the mechanisms of «radiation creep» for austenitic steel at temperatures below 450–470 °C after irradiation, significantly increasing the steel yield point, stricter treatment of models of steel deformation at irradiation and swelling in terms of classical approaches tried out in practice, appears to be important.

Let us write the strain tensor ε_{ij} $(i, j = x, y, z)$ as the sum

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p + \varepsilon_{ij}^c + \delta_{ij}\frac{S}{3}, \qquad (6)$$

where indices e, p, c pertain to elastic strain, instantaneous plasticity and creep.

In the general case for austenitic steels, when the volume of phase changes is small, elastic strain is reversible by definition, i.e. disappearing, if its cause is eliminated, and it is presented in the following form, according to Hooke's law [9]:

$$\varepsilon_{ij}^e = \frac{\sigma_{il} - \delta_{il}\sigma}{2G} + \delta_{il}[k\sigma + \alpha(T - T_0)] \quad (i, j = x, y, z),$$

where $G = E/(2(1 + \nu))$; ν is the Poisson's ratio; E is the modulus of normal elasticity; k is the coefficient of volume compression equal to $(1 - 2\nu)/E$; α is the coefficient of relative thermal expansion in temperature range $T(x, y, z)$ and T_0 (x, y, z, t_0).

For tensor of instantaneous plasticity strains ε_{ij}^p in modern commercial software the plastic flow law is usually used, which is associated with Mises yield condition [10], i.e.

$$d\varepsilon_{ij}^p = d\lambda(\sigma_{ij} - \delta_{ij}\sigma) \quad (i, j = x, y, z), \qquad (7)$$

where $d\lambda$ is the scalar function of x, y, z coordinates and time t, connecting increment of tensor ε_{ij}^p with stress deviator $(\sigma_{ij} - \delta_{ij}\sigma)$ by yield condition of the following form:

$$\begin{gathered} d\lambda = 0, \text{ if } f = \sigma_{eq}^2 - \sigma_y^2(\omega) < 0 \text{ or } f = 0, \text{ but } df < 0; \\ d\lambda > 0, \text{ if } f = 0 \text{ and } df \geq 0 \\ (f > 0 \text{ state is inadmissible}), \end{gathered} \qquad (8)$$

where σ_{eq} is the equivalent stress or stress intensity

$$\sigma_{eq}^2 = \frac{1}{2}(\sigma_{ij} - \delta_{ij}\sigma)(\sigma_{ij} - \delta_{ij}\sigma); \qquad (9)$$

$\sigma_y(\omega)$ is the material yield point at temperature T, radiation dose D and degree of strain hardening ω_p according to formulas (4) and (5).

For tensor of strains of diffusion plasticity or creep ε_{ij}^c the plastic flow law [10] is usually used in the following form:

$$d\varepsilon_{ij}^c = \Omega dt(\sigma_{ij} - \delta_{ij}\sigma) \quad (i, j = x, y, z), \qquad (10)$$

where Ω is the creep scalar function which is determined by value σ_{eq}^m $(m = 4–6)$ for material at a given temperature and extent of irradiation, i.e.

$$\Omega(\sigma_{eq}, T, D) = \Omega_q(T, D)\sigma_{eq}^m. \qquad (11)$$

In the works by the supporters of «radiation creep» approach the following relationship is used:

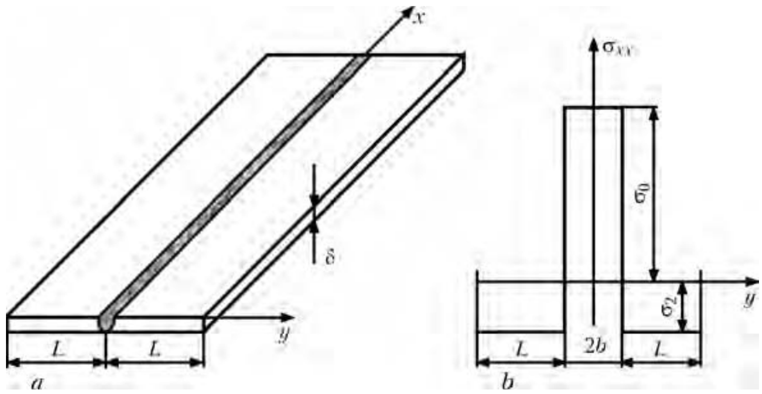

Figure 1. Schematic of austenitic steel strip with a weld (a), and distribution of residual stresses σ_{xx} (b)

$$\xi^c_{eq} - \left(B_0 \frac{dD}{dt} + \omega_0 \frac{dS_0}{dt}\right)\sigma_{eq}, \quad (12)$$

where ξ^c_{eq} is the rate of change of equivalent creep strain according to [9], i.e.

$$\xi^c_{eq} = \frac{\sqrt{2}}{3}\sqrt{\frac{d\varepsilon^c_{ij}}{dt}\frac{d\varepsilon^c_{ij}}{dt}}; \quad (13)$$

B_0, ω_0 are the material characteristics, little dependent on temperature [9]; $S_0 = S$ according to formula (1) at $f_2(\sigma) = 1$ and $f_3(\omega_p) = 1$.

From comparison of expressions (10) and (12) under conditions (9), (13) it follows that identity of equations (10) and (12) is in place at

$$\Omega = \frac{2}{3}\frac{\xi^c_{eq}}{\sigma_{eq}} = \frac{2}{3}\left(B_0 \frac{dD}{dt} + \omega_0 \frac{\partial S_0}{dt}\right) \quad (14)$$

or taking into account formula (11), provided B_0 and ω_0 are proportional to σ^m_{eq}. In [9], however, it is recommended that $B_0 = 1\cdot10^{-6}$ (MPa·dpa)$^{-1}$, $\omega_0 = 6\cdot10^{-3}$ MPa^{-1}, i.e. are constant.

Thus, the process of «radiation creep» is based on significant linearization of the connection between strains and stresses that may be acceptable for a narrow range of stress variation, or when direct experiments on determination of creep function of irradiated material confirm that m value in expression (11) is close to zero.

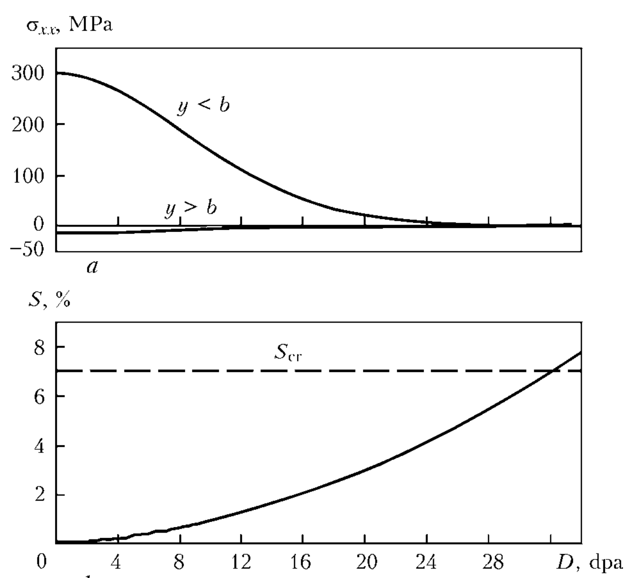

Figure 2. Kinetics of residual stress variation in the strip at L = = 20 cm, b = 1 cm, Q_x = 0; σ_0 = 300 MPa; $\sigma_2 = -300\, b/(L - b)$ (a), and change in swelling in zone y = 0 (b)

In this connection, it appears to be logical to apply a more conservative approach based on the assumption that at temperatures of RI element irradiation $T \le \le T_{max}$ = 470 °C austenitic material is characterized by a high creep resistance, i.e. in formula (10) creep function is equal to zero. The conservatism of this approach consists in higher risk of appearance of stresses close in their value to material yield point, considering the radiation and strain hardening [9].

The process of austenitic steel swelling is accompanied to a certain extent by relaxation of already formed stresses. It can be shown that instantaneous plasticity can well be the relaxation mechanism. The above phenomenon is readily modelled on such a simple example, as austenitic steel plate with a weld (Figure 1). Longitudinal residual stresses σ_{xx} are approximately described by the relationships

$$0 < |y| \le b,\ \ \sigma_{xx} = \sigma_0,\ \ b < |y| < L,\ \ \sigma_{xx} = -\frac{\sigma_0 b}{L - b}.$$

Plate temperature is constant and equal to 470 °C. Edges $y = \pm L$ are free, edge $x = 0$ is restrained, i.e. displacement $U_x(0, y) = 0$; edge $x = L_{x_L}$ is loaded by distributed forces q_x so that $\delta\int_0^L q_x dy = 2Q_x$, where δ is the plate thickness. Let us assume that $Q_x = q_x 2\delta$. Yield point of plate material, depending on strain hardening ω_p and radiation hardening, changes by a dependence given in [6]:

$$\sigma_y = 202 + 239\varepsilon\xi\pi\,[-2.22\cdot10^{-3}(T + 273\ ^\circ\mathrm{C})] + $$
$$+ 400\,[1 - \exp(-0.47D/D_0)]^{0.5},$$

where D_0 = 10/2.22 dpa.

Figures 2–4 give the results of swelling distribution across the welded joint at b = 1 cm, L = 20 cm and different Q_x values, as well as the respective changes of stresses in zones $0 < |y| < b$ and $b < |y| < < L$, depending on plate radiation dose and different

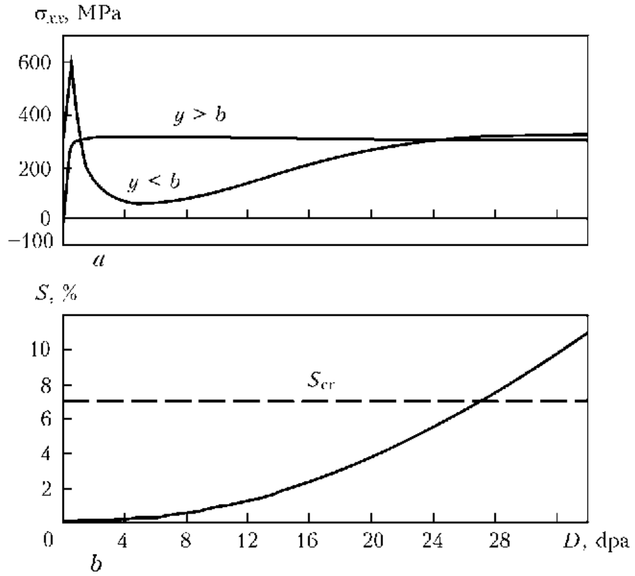

Figure 3. Kinetics of the change of residual stresses in the strip at L = 20 cm, b = 1 cm, $Q_x = 300L\delta H$; δ = 1 cm; σ_0 = 300 MPa; σ_2 = = $-300\ b/(L - b)$ (*a*), and change in swelling in zone $y = 0$ (*b*)

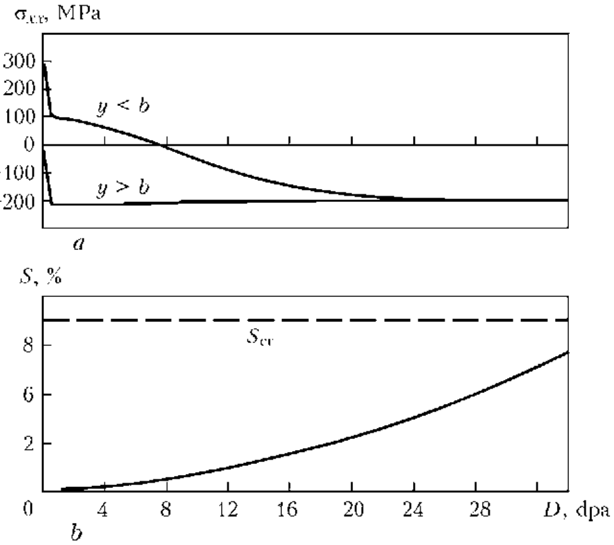

Figure 4. Kinetics of the change of residual stresses in the strip at L = 20 cm, b = 1 cm, $Q_x = -200L\delta H$; δ = 1 cm; σ_0 = 300 MPa; $\sigma_2 = -300\ b/(L - b)$ (*a*), and change in swelling in zone $y = 0$ (*b*)

Q_x values. It is seen that for an unrestrained plate at $Q_x = 0$ and radiation dose of more than 14 dpa the initial residual stresses are completely relaxed (forgotten). The same is noted also at $Q_x > 0$ (Figure 3). In case of a compressive external load (Figure 4) deceleration of this process occurs at the expense of correction $f_2(\sigma)$, which nonetheless proceeds owing to plastic flow by the mechanism of instantaneous plasticity without «radiation creep».

Note that the critical level of swelling, corresponding to 7 % [9], is achieved at favourable tension (see Figure 3) approximately during 35 years of operation of reflection shield elements, and at unfavourable compression (see Figure 4) — during a period of not less than 60 years (within the reflection shield of WWER-1000 reactor the average radiation dose after 30 years corresponds to 20 dpa).

Let us consider a more complex example of RI element of WWER-1000 reactor, when considerable gradients of radiation dose and respective gradients of swelling level are preserved in the element body for a long time (Figure 5). It should be noted that the data in Figure 5, *a* can to a certain extent be postulated for the shaft wall in the core. Shaft wall thickness is 60 mm, average exposure dose (point z = = 30 mm) by the data of [11] is equal to about 0.20 dpa per year. On the shaft inner surface $z = 0$, this value is close to average irradiance of the reflection shield, i.e. D = 1.5 dpa per year, and in point z = 60 mm radiation dose is equal to approximately 0.03 dpa after 30 years, i.e. approximately 0.001 dpa per year [11].

Here, the initial stressed state, connected with reaching the thermal conditions at reactor commissioning, was not taken into account. It was assumed that T = 470 °C (z = 0), T = 300 °C (z = 60 mm). As the temperature fields, determining this stressed state, become stationary after several days, temperature stresses related to them are also stationary of the type of initial (residual) ones, considered in Figures 2–4. Their interaction with swelling at developed plastic flow (high radiation dose) leads to the respective relaxation.

At reactor cooling (temperature homogenizing) new fields of residual stresses are formed, which are largely compensated at subsequent heating of the reactor. For postulated irradiation field (see Figure 5, *a*) dependence (1) was used to calculate the fields of volume strain of swelling. Their connection to the stressed state and accumulated plastic strain (corrections $f_2(\sigma)$ and $f_3(w_p)$) was taken into account. For this purpose an approach was used, which is based on successive tracing (depending on the field of radiation dose $D(x, y, z)$) of evolution of the field of swelling $S(x, y, z)$ (see Figure 5, *b*), displacements $U_j(x, y, z)$, strains $\varepsilon_{ij}(x, y, z)$ and stresses $\sigma_{ij}(x, y, z)$.

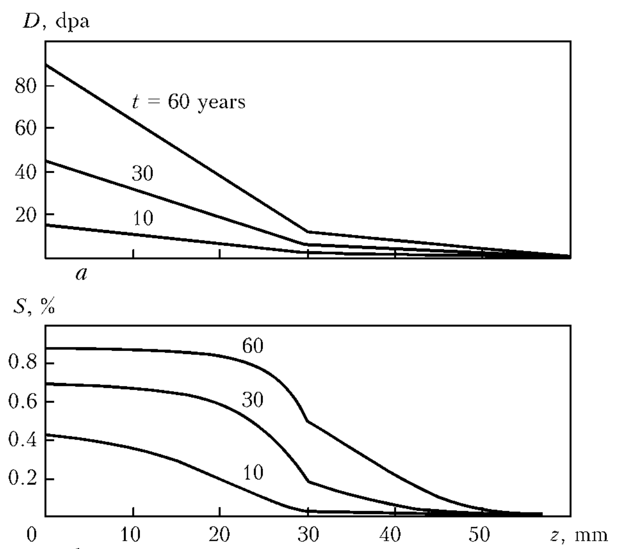

Figure 5. Distribution of radiation dose D (*a*) and swelling S (*b*) across wall thickness in different moments of time t

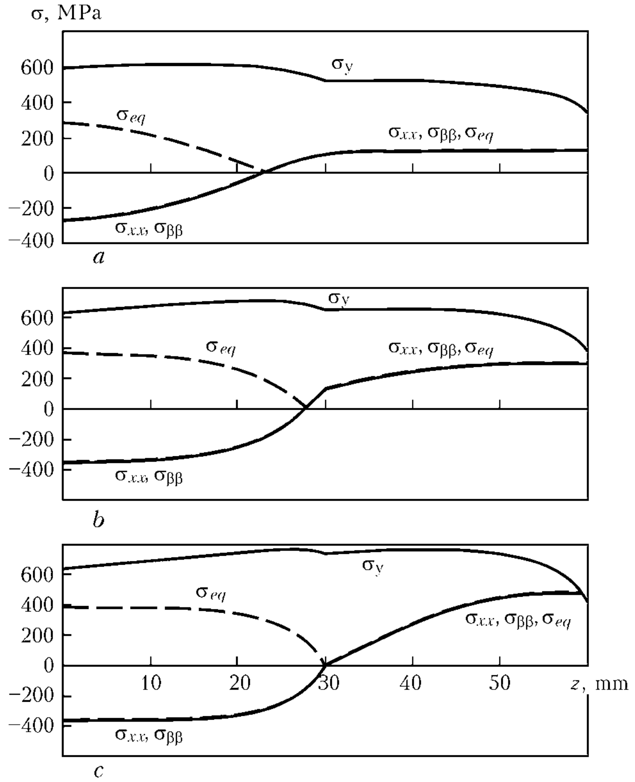

Figure 6. Distribution of stresses σ_{xx} (axial), $\sigma_{\beta\beta}$ (tangential), σ_{eq} (equivalent), yield point σ_y across wall thickness at $t = 10$ (*a*), 30 (*b*) and 60 (*c*) years

An implicit schematic of allowing for swelling from average normal stress σ was used. For this purpose dependence (6) was presented in the following form:

$$\varepsilon_{ij} = \varepsilon^e_{ij} + \varepsilon^p_{ij} + \frac{S_0}{3}(1 + p\sigma)\delta_{ij} = \bar{\varepsilon}^e_{ij} + \varepsilon^p_{ij} + \delta_{ij}\frac{S_0}{3}p, \quad (15)$$

where

$$\bar{\varepsilon}^e_{ij} = +\varepsilon^e_{ij} + \frac{S_0}{3}p\sigma\delta_{ij} =$$

$$= \frac{\delta_{ij} - \delta_{ij}\sigma}{2g} + \delta_{ij}\left[\left(K + \frac{S_0}{3}p\right)\sigma + \alpha(T - T_0)\right] (i, j = x, y, z),$$

which is equivalent to expression (15), if $\left(K + \frac{S_0}{3}p\right)$ $\overline{K}$ is used instead of K, that eliminates the need for S iterations.

Respective elastoplastic problems in each tracing step were solved in terms of ideology of «Weldpredictions» software package developed at the E.O. Paton Electric Welding Institute of NASU, i.e. with involvement of elastoplastic flow theory of Plandtl–Reuss, associated with Mises yield condition, i.e. with application of relationships (5)–(8), (14) and finite element method. Figure 6 gives fragments of the above tracing of stress-strain states in the shaft wall across its thickness, allowing for axial symmetry and in terms of shell hypotheses of Kirchhoff–Love in the core mid-height part.

It follows from the data in Figures 5, 6 that the zone of the most intensive irradiation (see Figure 5, *b*) adjacent to the shaft inner surface is in the compressed state by x and β, that, however, leads to a rather significant swelling (on the level of 0.3 %). Value of σ is small. Zone $30 < z < 60$ mm has a relatively low radiation dose and small swelling, respectively, that determines the respective distribution of stresses σ_{xx} and $\sigma_{\beta\beta}$. Nature of plastic strain development across the wall thickness related to swelling kinetics is quite specific. In fact, mainly elastic deformation occurs during 60 years. Plastic flow after 60 years arises in zone $x \approx 60$ mm, because of the low level of σ_y (small radiation dose).

CONCLUSIONS

1. Calculation methods, based on modern models of nonisothermal elastoplastic deformation of material, allow prediction of the stress-strain state of RI welded elements in nuclear power reactors of WWER-1000 type under the conditions of intensive irradiation, taking into account the process of material swelling.

2. Specific examples were used to show the possibility of predictive estimation of the residual safe operating life for individual RI elements based on the conditions of local critical swelling of material.

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