https://doi.org/10.37434/tpwj2021.03.02

MATHEMATICAL MODELING OF RESIDUAL STRESSES IN WWER-1000 ELEMENTS AFTER HEAT TREATMENT

O.V. Makhnenko[1], S.M. Kandala[1], N.R. Basystyuk[1] and M.V. Cherkashin[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]«UKRTsNIITMASh» Company
7a Vasylenka Str., 03124, Kyiv, Ukraine. E-mail: ukrcniitmash@ukr.net

Determination of residual life and extension of safe operating life of WWER-1000 internals for a term of up to 60 years beyond the design period is an important scientific and engineering objective for nuclear power industry of Ukraine. During long-term operation the reactor internal elements: reflection shield and cavity are exposed to intensive impact of damaging radiation dose that causes the processes of radiation embrittlement, swelling and creep in the material (08Kh18N10T austenitic steel). Technological residual stresses after welding and subsequent heat treatment should be taken into account at calculation-based substantiation of the safe operating life of reactor internal elements. In the work, mathematical modeling was used to derive residual stress distributions in the volume of the reflection shield and internal cavity after electroslag welding and their redistribution fields after the technological process of postweld heat treatment by the austenitizing mode. It is determined that the residual welding stresses are largely relaxed during austenitizing. In the reflection shield, however, which is of complex geometry with variable wall thickness and cooling channels, high residual stresses develop, due to occurrence of a significant temperature gradient at cooling during austenitizing. These stresses should be taken into account at determination of the residual life of WWER-1000 reactor internals. 8 Ref., 8 Figures.

Keywords: WWER-1000, reactor internals, reflection shield, internal cavity, electroslag welding, heat treatment, austenitizing, residual stresses

In keeping with design documentation, the elements of reactor internals (RI) of WWER-1000 power unit, namely reflection shield (RS) and internal cavity (IC) are welded structures from 08Kh18N10T austenitic steel. It is known that these structural elements are the most prone to neutron irradiation during long-term operation of the power unit. All the longitudinal welded joints of the above-mentioned RI elements were produced by the technology of electroslag welding (ESW), and IC circumferential welded joints were made by automatic submerged-arc welding.

In keeping with the requirements of normative documentation [1] all the made ESW joints of parts from steels of austenitic class should be subjected to postweld heat treatment by austenitizing mode specified for base metal. At overall heat treatment the welded items are completely placed into the furnace. In keeping with [2], the austenitizing process is steel heat treatment, similar to hardening of carbon steels, which consists of its heating up to the temperature of 1050–1100 °C, short-time soaking at this temperature and further rapid cooling. During heating, chromium and carbon carbides completely dissolve in austenite, while rapid cooling prevents repeated precipitation of carbides. However, in structures with complex geometry, such as RS (variable thickness, cooling channels, etc.), it may lead to appearance of a rather high temperature gradient in the cross-section due to non-uniform cooling and to formation of high residual stresses, accordingly.

At calculated substantiation of extension of WWER-1000 RI life beyond the design period (up to 60 years of operation and longer) it is necessary to take into account the technological residual stresses at structure fabrication. At present the questions of technological residual stresses are not sufficiently well-studied as regards RI elements [3].

Mathematical modeling of thermal processes and viscoelastoplastic deformation of material was used to perform numerical study of formation, relaxation and redistribution of residual stresses during welding and further heat treatment (austenitizing) of RS and IC of WWER-1000 power unit.

ESW technological parameters. Schemes of layout of RS and IC longitudinal welded joints, made by electroslag technology, are shown in Figure 1. Welded joint width is approximately 30 mm, ESW technological parameters, assumed in calculation, are given be-

O.V. Makhnenko — https://orcid.org/0000-0002-8583-0163, S.M. Kandala — https://orcid.org/0000-0002-2036-0498,
M.V. Cherkashin — https://orcid.org/0000-0003-0672-5443

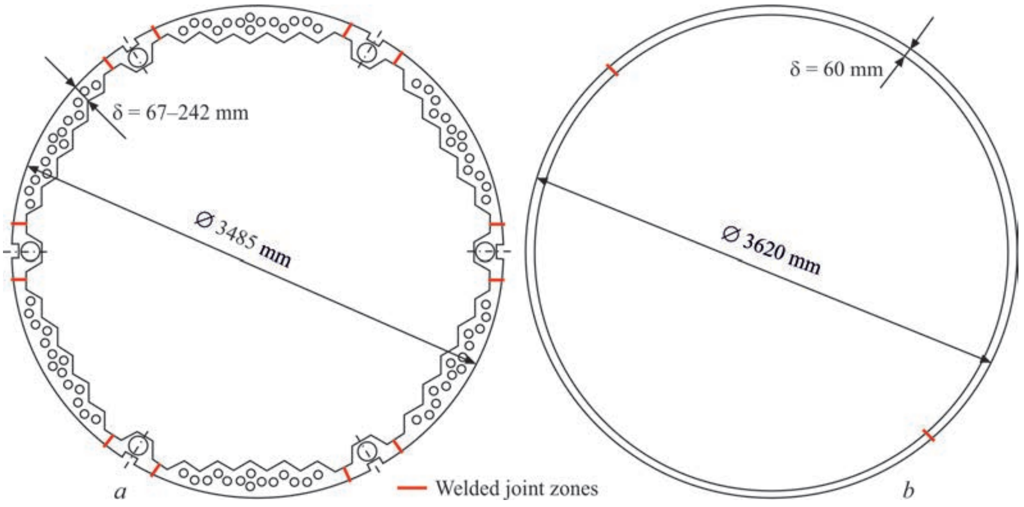

Figure 1. Layout of longitudinal welded joints in the RS (*a*) and IC (*b*) cross-section

low [3]. The power consumed in welding, is equal to approximately 9 kW, while ESW parameters provide sufficient power for heating (~60 %) and melting of weld metal (~40 %).

ESW technological parameters

Welding current, A	600
Voltage, V	46
Electrode feed rate, m/h	230
Welding speed, mm/s	0.42
Depth of liquid metal pool, mm	40
Temperature of liquid metal pool, °C	2000
Nozzle thickness, mm	10
Wire diameter, mm	3
Number of working electrode wires (which are duplicated), pcs	2/2
Flux	48-OF-6
Electrode wire grade	Sv-04Kh19NN11M3
Thermal efficiency of the process, %	85

Description of mathematical model for determination of SSS in welding. The problem of determination of SSS of RI elements was solved using finite element modeling. In view of large dimensions of RS and IC structural elements, as well as presence of cyclic symmetry in their structures, the developed finite-element models are 30 deg sectors, consisting of flat rectangular elements with face size not greater than 5 mm (Figure 2).

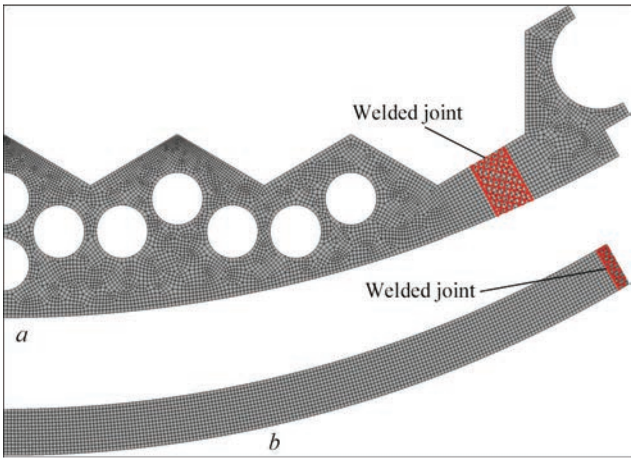

Figure 2. Finite-element models of RS (*a*) and IC (*b*) in 2D definition

The temperature fields at ESW were modeled using the equation of nonstationary heat conductivity, which includes calculation of bulk welding heat source $W(x, y, z, t)$:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+ +W(x, y, z, t)=c\rho\frac{\partial}{\partial}, \qquad (1)$$

where ρ is the material density; c is the specific heat capacity; λ is the coefficient of heat conductivity; T is the material temperature.

The temperature problem was solved with the assumption of quickly-moving heat source that allowed using the two-dimensional finite element model in the RS and IC cross-section.

Boundary conditions on the surfaces of RI elements, allowing for the convective heat exchange with the environment, were assigned in the following form:

$$q=-h(T_{\text{out}}-T), \qquad (2)$$

where T_{out} is the ambient temperature; q is the heat flow; h is the coefficient of heat transfer from the surface at convective heat exchange with the environment.

Initial conditions at $t = 0$:

$$W(x, y, z, 0)=, \quad T=20\ ^{\circ}\mathrm{C}, \quad T_{\text{out}}=20\ ^{\circ}\mathrm{C}. \qquad (3)$$

Taking into account the «plane strain» hypothesis, solution of the problem for determination of the distributions of spatial components of stresses and strains was obtained using two-dimensional models of RS and inner cavity cross-section in the elastoplastic definition, i.e. the strain tensor can be presented as a sum of tensors [4]:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} (i,\ j) = x,\ y,\ z, \qquad (4)$$

where ε_{ij}^{e} is the elastic strain tensor; ε_{ij}^{p} is the plastic strain tensor.

Components of tensors of stresses σ_{ij} and elastic deformations ε_{ij}^{e} are related to each other by Hooke's law:

$$\varepsilon_{ij}^{e} = \frac{\sigma_{ij} - \sigma_{ij}\sigma}{2G} + \delta_{ij}(K\sigma + \varphi), \qquad (5)$$

where δ_{ij} is the unit tensor ($\delta_{ij} = 0$, if $i \neq j$, $\delta_{ij} = 1$, if $i = j$), $\sigma = \frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$, $G = \frac{E}{2(1+\nu)}$ is the shear modulus; $K = \frac{1-2\nu}{E}$ is the bulk compression module; E is the Young's modulus; v is the Poisson's ratio; φ is the function of free relative elongations caused by temperature change:

$$\varphi = \alpha(T - T_0), \qquad (6)$$

where α is the coefficient of relative temperature elongation of material.

Plastic strains are related to the stressed state by an equation of the theory of plastic nonisothermal flow, associated with Mises flow condition:

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

where $d\varepsilon_{ij}^{p}$ is the increment of ε_{ij}^{p} tensor at the given moment of time t, due to the deformation history, stresses σ_{ij} and temperature T; $d\lambda$ is the scalar function which is determined by the flow conditions in the following form:

$$\begin{gathered} d\lambda = 0, \text{ if } f = \sigma_i^2(T) < 0 \text{ or } f = 0, \text{ at } df ,0; \\ d\lambda > 0, \text{ if } f = 0 \text{ and } df > 0; \\ \text{state } f = 0 \text{ is inadmissible,} \end{gathered} \qquad (8)$$

where σ_i is the stress intensity

$$\sigma_i = \frac{1}{\sqrt{2}}\Big[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{xx} - \sigma_{zz})^2 + \\ +(\sigma_{yy} - \sigma_{zz})^2 + 6(\sigma_{xy}^2 + \sigma_{xz}^2 + \sigma_{xz}^2)\Big]^{\frac{1}{2}},$$

$\sigma_y(T)$ is the yield limit of the material at temperature T.

Equation (7) shows that in order to obtain the results on the components of residual stresses σ_{ij} and strains ε_{ij}, it is necessary to consider the process of development of elastoplastic strains with time, starting from a certain initial state. The method of sequential tracking is traditionally used for this purpose, when for moment t the solution is sought, if complete solution for $(t - \Delta t)$ moment is known, where Δt is the step of tracking the development of elastoplastic strains, within which it can be approximately assumed that this development occurs by a rather simple loading trajectory. In this case, the connection between end increments of the strain tensor $\Delta\varepsilon_{ij}$ and stress tensor σ_{ij}, in keeping with [4] can be written as:

$$\Delta\varepsilon_{ij} = \psi(\sigma_{ij} - \delta_{ij}\sigma) + \delta_{ij}(K\sigma) - b_{ij}, \qquad (9)$$

where ψ is the function of the state of material in point (x, y, z) at moment t.

$$\begin{gathered} \psi = \frac{1}{2G}, \text{ if } f < 0, \quad \psi = \frac{1}{2G}, \text{ if } f = 0, \\ \text{state } f = 0 \text{ is inadmissible,} \end{gathered} \qquad (10)$$

b_{ij} is the tensor function of additional strains, which is determined by increase of $\Delta\varphi$ and known results of the previous tracking step:

$$b_{ij} = \left[\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}(K\sigma)\right]_{t-\Delta t} + \\ +\delta_{ij}\Delta\varphi(i,\ j = x,\ y,\ z). \qquad (11)$$

Flow conditions in the form of (7) include significant nonlinearity of the function of material state ψ. The iteration processes are usually used for realization of this type of physical nonlinearity. As a result, at each iteration, the physically nonlinear problem becomes a linear problem of the type of the problem of the theory of elasticity with a variable shear modulus, which is equal to $\frac{1}{2\psi}$, and additional strains b_{ij}. Such a linearized problem is solved using the numerical methods.

Results of modeling the residual stresses at ESW. The developed finite-element mathematical models, taking into account the given technological parameters of ESW and geometrical characteristics of RI elements, were the base for deriving the calculated distributions of temperatures and stresses at different moments of time from the beginning of welding and up to the residual state. Figure 3 shows the distributions of maximum temperatures, when making the longitudinal welded joints of the RS and IC during welding. Even taking into account the features characteristic for single-pass ESW of thick elements, heating is of a local nature with a high temperature gradient in the circumferential direction.

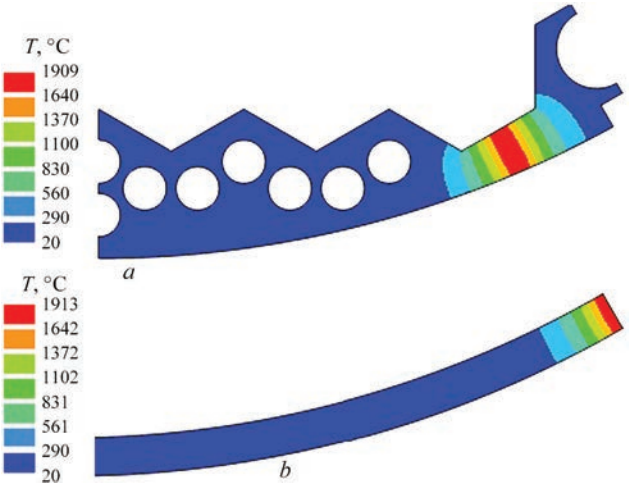

Figure 3. Calculated distributions of maximum temperatures when making longitudinal welded joints of RS (*a*) and IC (*b*)

Obtained results of mathematical modeling of the stressed state showed that the local high-temperature heating at ESW and further cooling leads to formation in the considered RI elements of high residual stresses of up to 230 MPa in the axial direction in the weld zone (Figure 4, *e*, *f*), i.e. up to material yield limit, and to a lower level of residual stresses of up to 50 MPa in the radial (Figure 4, *a*, *b*) and circumferential (Figure 4, *c*, *d*) directions, owing to uniformity of welding heating across the thickness at ESW. Considering the rather large zone of high tensile residual stresses after welding both in the RS and in the IC, it is rational to conduct postweld heat treatment by the austenitizing mode, in order to lower the level of residual welding stresses and to ensure dissolution of chromium and carbon carbides, which form in the HAZ in welding.

Heat treatment modeling. Welded joints of critical structures are subjected to postweld heat treatment. In keeping with the requirements of normative documentation [1], the welded joints of structural elements of NPP equipment from austenitic steel are subjected to heat treatment by the mode of austenitizing (hardening).

In keeping with [5], austenitizing (hardening) of the items should be conducted by the following mode: heating to 1050–1100 °C, parts with up to 10 mm material thickness should be cooled in air, those of more than 10 mm thickness — in water. Complex-shaped welded items should be cooled in air to avoid deformations. Soaking time at heating during hardening is 30 min for items with wall thickness of up to 10 mm, for those of more than 10 mm it is 20 min, +1 min per 1 mm of maximum thickness. The thickness of RS and IC in the welded joint zone is 67 and 60 mm, respectively. Thus, cooling of RI elements during austenitizing was to take place in air and soaking time should be approximately 87 min for the RS and 80 min for the IC.

When conducting mathematical modeling of the process of postweld heat treatment of RI elements, a feature of the developed model for determination of the nonstationary temperature field was convective

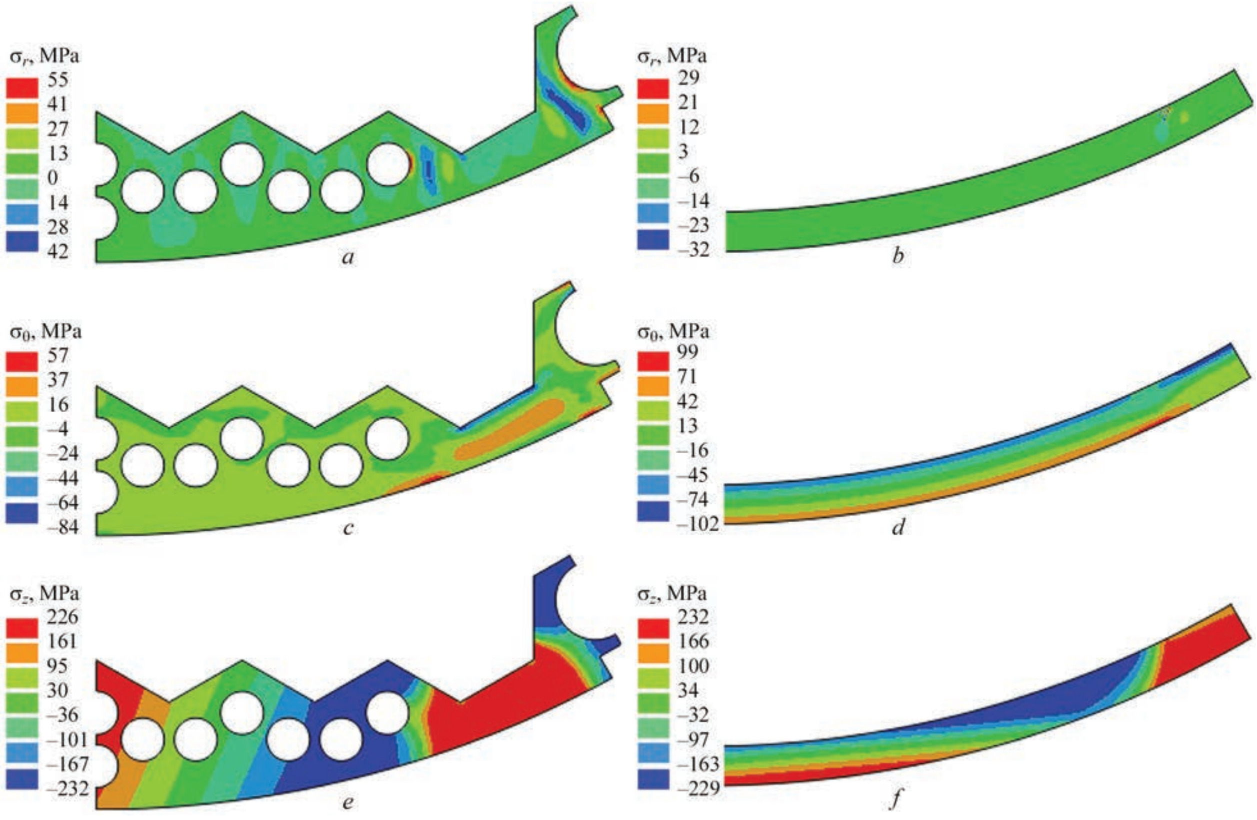

Figure 4. Residual stresses after welding the rings of RS and IC in the radial (*a*, *b*), circumferential (*c*, *d*) and axial (*e*, *f*) directions

heat exchange on the surfaces due to gradual heating of the environment (air) in the furnace, and further rather fast cooling in air. The nonstationary boundary conditions corresponded to uniform increase of the ambient temperature during heating and rapid temperature lowering to 20 °C at cooling.

The heat treatment schedule, namely, changes of ambient temperature during austenitizing of RI elements in the furnace at heating at the rate of 30 °C/h, soaking for 87 min and cooling at a higher rate in air is shown in Figure 5.

Initial and boundary conditions of the boundary value problem of determination of temperature distributions in the RS and IC at heat treatment:

$$\text{at } t = 0\ T_{\text{out}}(0) = 20\ °\text{C},\ T(0) = 20\ °\text{C}$$

$$q = -h(T_{\text{out}}(t) - T),\ T_{\text{out}}(t) = 30\ °\text{C/h}\cdot t,$$

$$T_{\text{out}}^{\max} = 1100\ °\text{C}.$$

The coefficient of heat transfer from the surfaces of RI elements at convective heat exchange with the environment in the furnace or in air was taken equal to the value of $h = 30$ W/(m^2·°C) under the conditions of natural convection and constant in the entire range of heating and cooling temperature. Radiant heat exchange in the developed model was not modeled separately, and its contribution was taken into account in a certain increase of the heat transfer coefficient.

The long process of heating of welded structural elements to austenitizing temperature causes the processes of high-temperature creep in the material, leading to relaxation of residual stresses in the welded joint zone.

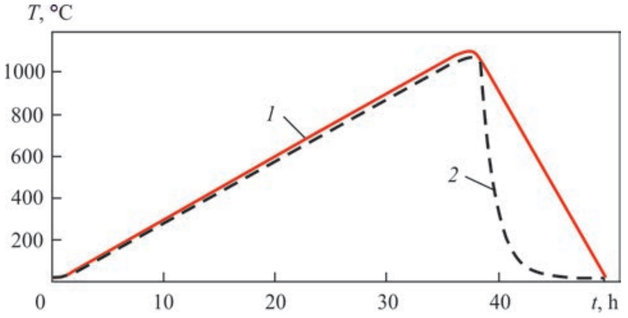

Figure 5. Plot of the change of temperature of RI element material during heat treatment by austenitizing mode: *1* — austenitizing mode; *2* — calculated temperature

In the developed model the problem of determination of SSS at heat treatment was solved in the viscoelastoplastic formulation [4]:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{\text{cr}}\ (i,\ j = x,\ y,\ z),$$

where the creep strain rate was determined using Bailey–Norton law [6]

$$\dot{\varepsilon}_{ij}^{\text{cr}} = A\sigma_{\text{eq}}^{n}. \tag{12}$$

For 08Kh18N10T austenitic steel at the temperature of 700 °C (973 K) the following coefficients can be taken: $A = 6.948\cdot10^{-14}$, $n = 6.22$ at determination of the rate of temperature creep strain [7]. In view of absence of data on creep of RI element material at higher temperatures in the developed model of determination of their SSS at heat treatment the abovementioned coefficients were taken for the entire high-temperature heating range above 700 °C temperature. This raises the conservatism of the calculation results, as at higher temperatures the creep processes proceed more intensively.

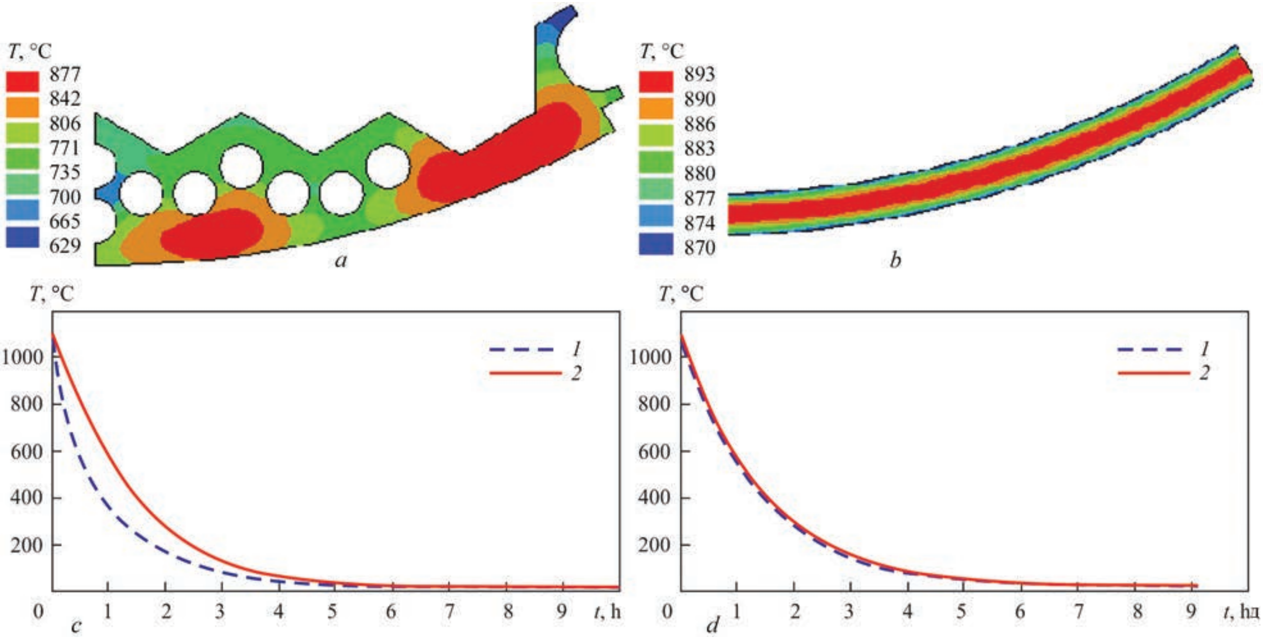

Figure 6. Temperature field at a certain moment of time and temperature change during cooling at austenitizing: *a*, *c* — RS; *b*, *d* — IC (*1* — on the surface; *2* — internal volume)

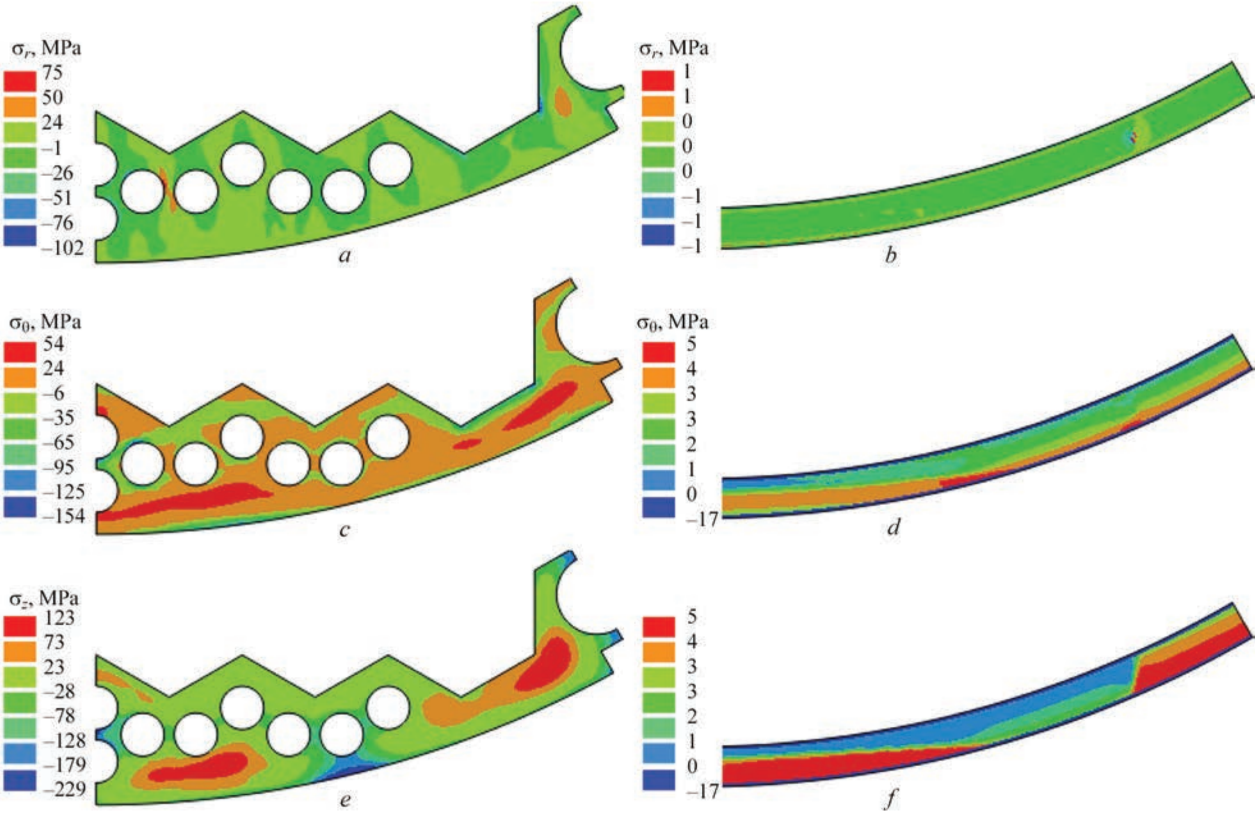

Figure 7. Residual stresses after welding and austenitizing of RS and IC in the radial (*a*, *b*), circumferential (*c*, *d*) and axial directions (*e*, *g*)

It should be noted that the RS cross-section differs from that of the IC by its nonuniform thickness, as the internal surface of the RS follows the reactor core boundary, while the presence of cooling channels promotes cooling of RS material in operation. Such geometrical irregularity influences the nonuniform cooling of the structure as a result of intensive heat exchange from the surfaces during cooling in air at heat treatment, that creates a temperature gradient of up to 250 °C (Figure 6, *a*, *c*) on the RS boundaries and in its internal volume, and, consequently, leads to formation of residual stresses after the austenitizing process (Figure 7, *a*, *c*, *e*). The inner cavity, owing to a uniform wall thickness, is characterized by a constant temperature gradient in the radial direction and absence of the gradient in the circumferential direction.

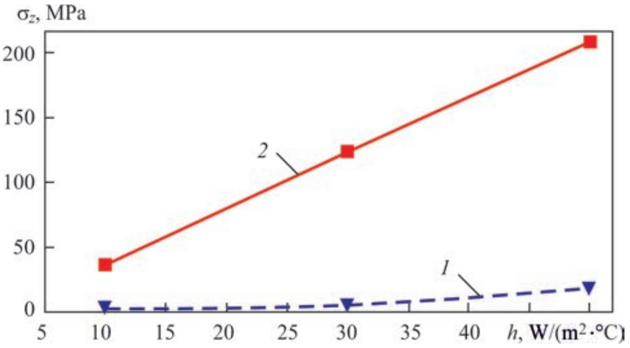

Figure 8. Level of residual axial stresses, depending on the value of heat transfer coefficient: *1* — IC; *2* — RS

Temperature difference on the surfaces and in the internal volume during cooling in air at heat treatment is not higher than 25 °C that does not lead to formation of high residual stresses (Figure 7, *b d*, *f*).

In the RS the highest residual stresses, both compressive (up to –230 MPa) and tensile (up to 120 MPa) are observed in the axial direction (Figure 7, *e*), and in the circumferential direction tensile residual stresses reach 55 MPa. Such a high level of residual stresses must be taken into account during determination of the residual life of RI elements when conducting the calculation-based substantiation of extension of the service life of WWER-1000 reactors.

As regards the IC, as a result of postweld heat treatment by austenitizing mode the residual welding stresses relax almost completely during long-term heating up to high temperatures, and rather low residual stresses in the range of (–17–5) MPa (Figure 7, *b*, *d*, *f*) form at the stage of rapid cooling, taking into account the low temperature gradient by thickness (Figure 6, *b*, *d*), due to IC regular cylindrical shape with a constant wall thickness. Such a low level of residual stresses cannot be ignored at calculation-based determination of the residual life of RI elements.

It should be noted that there is little published data, describing the temperature dependence of the coefficients of heat transfer from the surface of stainless steel parts at heating up to high temperatures. In keeping with [8], the coefficient of heat transfer at still air cooling can reach 150 W/(m²·°C) for 1100 °C temperature. In such a case high residual plastic strains and stresses can form at cooling of RI elements during austenitizing.

Evaluation of the effect of average coefficient of heat transfer from the surface assumed in calculations, on the level of maximum residual stresses after RS and IC heat treatment by the austenitizing mode was performed. Modeling was conducted at the values of average coefficient of heat transfer of 10, 30 and 50 W/(m²·°C). Figure 8 shows the dependence of the level of maximum residual stresses in the axial direction on the coefficient of heat transfer, which is characterized by a considerable rise at increase of the coefficient of heat transfer. For a more accurate assessment of the effect of austenitizing process on residual stresses in RI elements, it is necessary to have precised coefficients of heat transfer for stainless steel. Taking them into account can have a considerable effect on determination of the residual life of WWER-1000 RI.

Conclusions

1. At calculation-based substantiation of extension of the life of WWER-1000 RI beyond the design period (up to 60 years of operation and longer), it is necessary to take into account the technological residual stresses. Mathematical modeling of thermal processes and viscoelastoplastic deformation of the material was used to perform a numerical study of formation, relaxation and redistribution of residual stresses during welding and further heat treatment of structural elements of WWER-1000 RS and IC.

2. Results of mathematical modeling showed that postweld heat treatment of RI elements (RS and IC) by the austenitizing mode ($T = 1100$ °C) allows significantly relaxing the residual welding stresses. However, high geometrical irregularity of the RS affects the nonuniformity of cooling in the structure volume at intensive heat exchange in air that leads to appearance of a temperature gradient and, consequently, formation of high residual stresses that should be taken into account at determination of the life of WWER-1000 RI.

1. (1989) PNAE G-7-009–89: *Equipment and pipelines of nuclear power installations. Welding and overlaying, general provisions*. Moscow, ENERGOATOMIZDAT [in Russian].
2. Rakhmilevich, Z.Z., Radzin, I.M., Faramazov, S.A. (1985) *Reference book of mechanics of chemical and petrochemical production*. Moscow [in Russian].
3. Makhnenko, O.V., Mirzov, I.V., Porokhonko, V.B. (2016) Modeling of residual stresses, radiation swelling and stressed state of in-service WWER-1000 reactor baffle. *The Paton Welding J.*, **4**, 32–38. DOI: https://doi.org/10.15407/tpwj2016.04.03
4. Makhnenko, V.I. (1976) *Computational methods of investigation of welded stress and strain kinetics*. Kiev, Naukova Dumka [in Russian].
5. (2004) STP 26.260.484–2004: *Heat treatment of corrosion-resistant steels and iron-nickel-based alloys in chemical engineering*. OJSC «NIIKHIMMASH» [in Russian].
6. Rabotnov, Yu.N. (1966) *Creep of structural elements*. Moscow, GIFML [in Russian].
7. Margolin, B.Z., Gulenko, A.G., Kursevich, I.P., Buchatskii, A.A. (2006) Modeling for fracture in materials under long-term static creep loading and neutron irradiation. Pt 2: Prediction of creep rupture strength for austenitic materials. *Strength of Materials*, 38(**5**), 449–457.
8. Nemchinskiy, A.L. (1953) *Thermal calculations of heat treatment*. Leningrad, Sudpromgiz [in Russian].

Received 01.03.2021