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MATHEMATICAL MODELING OF RESIDUAL STRESSES IN COMPOSITE WELDED JOINTS OF WWER-1000 REACTOR VESSEL COVER WITH CSS NOZZLES

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ABSTRACT

Composite welded joints (CWJ) of the WWER-1000 reactor vessel cover with the nozzles of the control safety system (CSS) is the object of calculations of strength in the feasibility study of life extension of NPP power units. Kinetics of formation of residual stresses in welding CWJ of the WWER-1000 reactor vessel cover with the CSS nozzles and also their redistribution as a result of postweld heat treatment were calculated by mathematical modeling using finite element method. Effect of preheating on microstructural phase transformations in the HAZ of base material of the cover and nozzle was studied. The main features of residual stress distribution in CWJ after welding and after heat treatment were determined.

KEY WORDS: composite welded joint, reactor vessel cover, WWER-1000, HAZ, microstructural phase transformations, residual stresses, heat treatment, mathematical modeling

INTRODUCTION

One of the most important issues of safe operation and extension of the life of equipment of nuclear power plants (NPPs) in Ukraine is the issues of evaluation of strength, integrity and serviceability of welded joints, which requires data on residual stresses.

In the elements of equipment and pipings of existing NPPs, the so-called composite welded joints (CWJ) of dissimilar materials, usually steels of ferritic-pearlitic (or bainitic) and austenitic classes, were widely used. The peculiar feature of CWJ consists in the fact, that due to the difference in the chemical composition of the base and welding materials during welding heating, a significant diffusion of chemical elements in the joining area can occur, causing chemical and structural heterogeneity of CWJ metal [1, 2], and also due to a significant difference in the coefficients of thermal expansion in the materials of the constituent components in the process of welding and postweld heat treatment, significant unrelaxed residual stresses occur [3, 4]. Structural heterogeneity of CWJ metal and unrelaxed residual stresses significantly affect strength, service life and corrosion resistance of equipment elements [5]. Significant difficulties in the experimental measurement of unrelaxed residual stresses complicate their accounting when determining the life of equipment elements in NPPs.

The reactor vessel is one of the main elements, on the technical condition of which the life of safe operation of a nuclear power plant depends and which cannot be replaced. Welded joints in reactor vessel are problem areas, where the risk of defects has a high probability. While much attention was paid to the welded joints and deposits of the WWER-1000 reactor vessel, CWJ of the reactor vessel cover with the nozzles of the control safety system (CSS) almost were not studied. In addition to evaluation of structural integrity of the vessel cover in CWJ areas during long-term operation, analysis of the possibility of repair replacement of nozzles by welding technology in case of its wear also represents interest in the future.

DESIGN AND TECHNOLOGY OF CWJ OF VESSEL COVER WITH CSS NOZZLES

Figure 1 shows a scheme of welded joint of the cover of the WWER-1000 reactor vessel, which is formed by joining the CSS nozzle of steel 20 (pearlite class) and the reactor vessel cover of steel 15Kh2NMFA (bainite class) by welding material 10Kh16N25AM6 (austenite class), with the preliminary cladding 3I0-8 (austenite class). The inner surface of the CSS nozzles is insulated from the contact with the heat carrier by welded-on jackets of steel 08Kh18N10T. Welding of a jacket onto the nozzles was carried out during heating of a jacket and a nozzle to the temperature of 100 °C. On the lower part (ends) of the nozzles, an austenitic layer is deposited. In the Table 1 materials are shown, which were used in the manufacture of cover and nozzles of the upper block of the power unit WWER-1000 reactor [6–8].

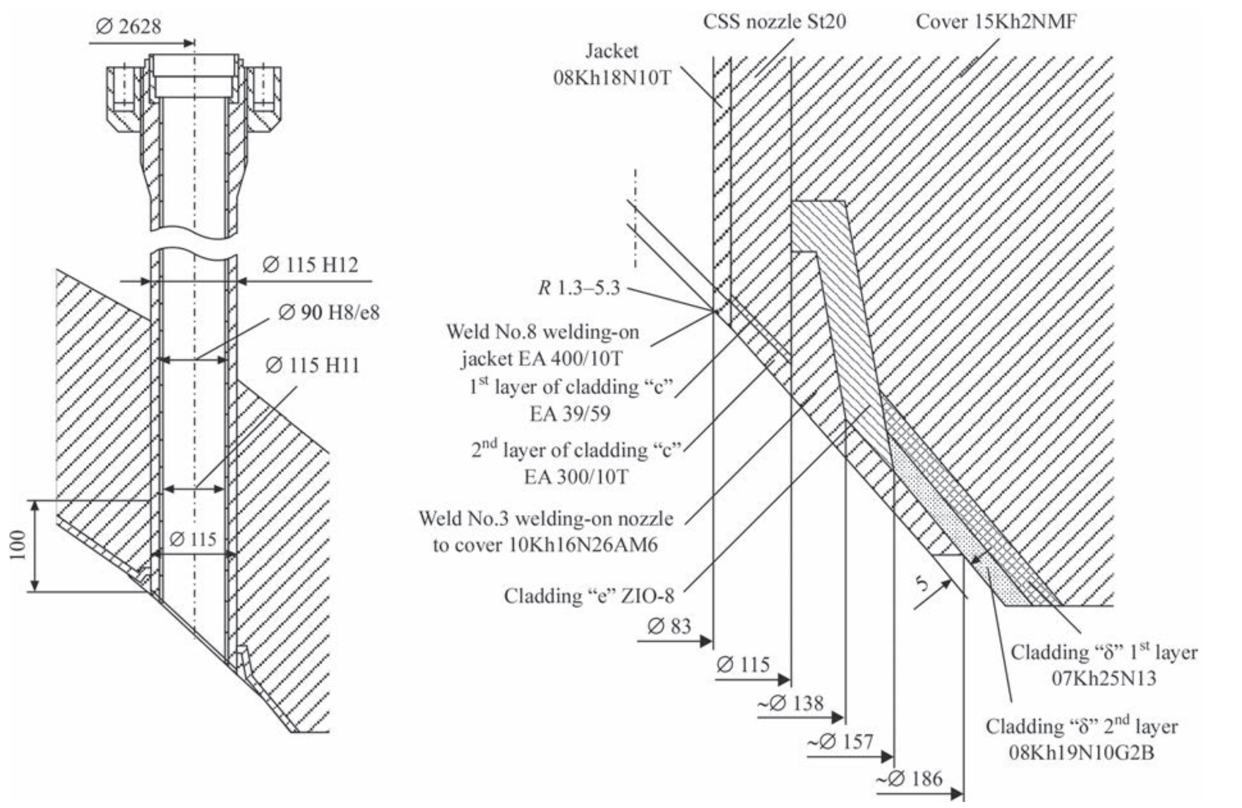

Figure 1. Reactor cover element with connected CSS nozzle and scheme of CWJ

DEVELOPMENT OF MATHEMATICAL MODEL OF SSS IN WELDING CWJ

To calculate the residual stresses, a 2D finite element model of joining the cover of the reactor vessel with a CSS nozzle, admitting axial symmetry (Figure 1), was constructed. The scheme of the model of the welded joint, boundary conditions and finite element mesh are shown in Figures 2, 3.

The temperature problem was solved, admitting a fast-moving heating source, which allowed using a two-dimensional finite element model in the cross-section of the welded joint (Figure 2). For simulation of temperature distributions while producing welding passes, an equation of non-stationary thermal conductivity was used, which includes taking into account the volumetric welding source of heating $W(x, y, t)$ [9]

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

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

$$W\ (x,y,t)=\frac{6Q}{ab\sqrt{\pi}}\exp\left(\frac{-3(x-x_0)^2}{a^2}-\frac{-3(y-y_0)^2}{b^2}\right), \quad (2)$$

Table 1. Materials used for the welded joint of the reactor cover with the CSS nozzles of the WWER-1000 reactor power unit [6–8]

Parts of cover with nozzles	Grade of material
Basic materials	
Reactor cover	15Kh2NMFA
CSS nozzles	20
Jacket of CSS nozzles	08Kh18N10T
Welding (cladding) materials	
Weld for welding-on CSS nozzles to the cover (No.3)	Sv-10Kh16N26AM6 and 3I0-8
Lower weld for welding-on jacket to the nozzle with cladding (No. 8)	EA-400/10T
1st layer of cladding “c” to the nozzle	EA-395/9
2nd layer of cladding “c” to the nozzle	EA-400/10T
Cladding “e” on the cover	ZIO-8
1st layer of cladding “δ” on the cover	07Kh25N13
2nd layer of cladding “δ” on the cover	08Kh19N10G2B

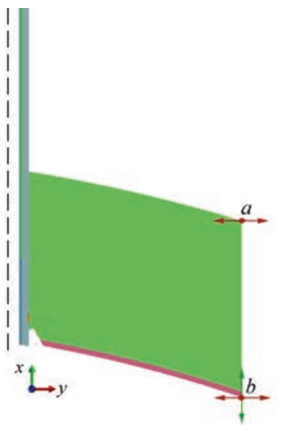

Figure 2. Boundary conditions and scheme of 2D model of CWJ: a — restricts movement in the horizontal plane; b — restricts movement in the horizontal and vertical planes

where Q is the effective power of the welding source of heating; x_0, y_0 are the coordinates of the center of the heating source; a, b are the corresponding dimensions (width and depth) of the effective heating zone in the directions x, y.

The time of heating the metal of each welded or deposited pass in the cross-section of the welded joint depends on the speed of welding v_w and the size of the effective heating zone a, i.e., in the first approximation it can be equal to $t_w = a/v_w$.

The parameters of the welding source of heating were chosen in such a way that the temperature of the metal in the weld exceeded the melting point, and the time interval between the passes was sufficient to cool the metal to the temperature of the accompanying heating.

The boundary conditions on the surfaces of welded joint elements taking into account the convection heat transfer with the environment were specified in the form:

$$q = -h(T_{out} - T), \tag{3}$$

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

Initial conditions at $t = 0$:

$$W(x, y, o) = 0,\ T_{heating} = 20\text{–}200\ °\text{C},$$
$$T_{out} = 20\ °\text{C}, \tag{4}$$

where $T_{heating}$ is the temperature of preliminary and accompanying heating.

Taking into account the hypothesis of "plane deformation", the solution of the distribution of spatial components of stresses and deformations was obtained by means of a two-dimensional model of the cross-section of the welded joint in an elastoplastic formulation, i.e., a deformation tensor can be presented in the form of the tensors:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \quad (i,j = x, y, z), \tag{5}$$

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

The components of stress tensors σ_{ij} and elastic deformations ε_{ij}^{e} are connected with each other by the Hooke's law:

$$\varepsilon_{ij}^{e} = \frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}(K\sigma + \varphi), \tag{6}$$

where δ_{ij} is a single tensor ($\delta_{ij} = 0$ if $i \neq j$, $\delta_{ij} = 1$, if $i = j$), $\sigma = \frac{1}{3}(\sigma_{xx} + \sigma_{yy} + \sigma_{zz})$; $G = \frac{E}{2(1+\nu)}$ shear modulus; $K = \frac{1-2\nu}{E}$ is the compliance of a volume compression; E is the Young modulus; ν is the Poisson's ratio; φ is the function of free relative elongations (volumetric changes) caused by changes in temperature and microstructural phase changes.

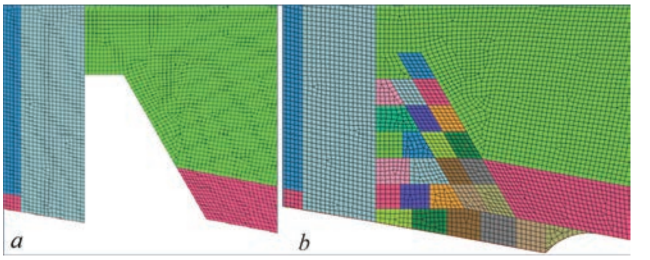

Figure 3. Finite element mesh in the CWJ zone: *a* — before welding; *b* — after welding

In a simple case, when structural transformations do not occur:

$$\varphi = \alpha(T - T_0), \tag{7}$$

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

In welding of steels that are sensitive to the thermal cycle of welding, in HAZ structural transformations with noticeable volumetric changes may occur. Their taking into account mainly affects the kinetics of distribution of welding stresses and deformations. The total effect of volumetric changes from the temperature T_0 to $T(t)$ is determined in the form [9]:

$$3\varphi = \frac{\sum V_j(T,t)\gamma_j(T) - \sum V_j(T_0)\gamma_j(T_0)}{\sum V_j(T_0)\gamma_j(T_0)} \quad (j = \text{A, F, P, B, M}), \tag{8}$$

where j phase is austenite, ferrite-pearlite, bainite, martensite; $\gamma_j(T)$ is the volume of the unit of mass of the j^{th} phase at the temperature T; $V_j(T)$ is the fraction (in fractions from the unit) of the j^{th} phase at the temperature T.

The values $\gamma(T)$ for low-alloy steels are given depending on carbon content C, % [10]:

$$\gamma_A(T) = 0.12282 + 8.56\cdot10^{-6}(T - 20) + 2.15\cdot10^{-3}\ \text{C},\ (\text{cm}^3/\text{g});$$
$$\gamma_M(T) = 0.12708 + 4.448\cdot10^{-6}(T - 20) + 2.79\cdot10^{-3}\ \text{C},\ (\text{cm}^3/\text{g}); \tag{9}$$
$$\gamma_{B,FP}(T) = 0.12708 + 5.528\cdot10^{-6}(T - 20),\ (\text{cm}^3/\text{g}).$$

The results of calculation of the mass fraction of each $V_j(T)$ phase in the final microstructure after cooling depend on the cooling rate in the characteristic range of temperatures (cooling rate from the temperature 800 to 500 °C).

Kinetics of changing the value $V_j(T)$ in the temperature range from T_s^j beginning of the appearance of the j^{th} phase to T_e^j — end of the appearance of the

j^{th} phase when the austenite decomposition is determined on the basis of ratios:

$$V_j(T) = V_j^{\max}\left[1-\exp\left(a_j\frac{T_{sj}-T}{T_{sj}-T_{ej}}\right)\right] \tag{10}$$

$$a_j = -2.7 \; (j = \text{M, FP, B});$$

$$V_a(T) = 1 - \sum_{\text{ì ,ôï ,á}} V_j(T)\,; \tag{11}$$

where $V_a(T)$ is the content of residual austenite at a temperature T.

The values of the temperatures of start T_{sj} and end T_{ej} of the types of j phase transformations were determined according to existing thermokinetic diagrams or the diagrams of the anisothermal decomposition of austenite (ADA) of the relevant steels.

Plastic deformations are associated with the stressed state of the equation of the theory of plastic nonisothermal flow, associated with the von Mises yield criterion:

$$d\varepsilon_{ij}^{p} = d\lambda\cdot(\sigma_{ij}-\delta_{ij}\sigma)\;(i,j = x,y,z)\,, \tag{12}$$

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

$$\begin{gathered} d\lambda = 0, \text{ if } f = \sigma_i^2 - \sigma_T^2(T) < 0 \text{ or } f = 0, \\ \text{at } df < 0; \\ d\lambda > 0, \text{ if } f = 0 \text{ i } df > 0; \\ \text{state } f > 0 \text{ is unacceptable,} \end{gathered} \tag{13}$$

where σ_i is the intensity of stresses

$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_{xx}-\sigma_{yy}\right)^2 + \left(\sigma_{xx}-\sigma_{zz}\right)^2 + \left(\sigma_{yy}-\sigma_{zz}\right)^2 + 6\left(\sigma_{xy}^2+\sigma_{xz}^2+\sigma_{yz}^2\right)}\,,$$

$\sigma_T = (T)$ is the yield strength of material at a temperature T.

Equation (8) shows, that in order to obtain the results on residual stress components σ_{ij} and deformations ε_{ij} it is necessary to consider the process of propagation of elastoplastic deformations by time, starting from some initial state. For this purpose, a method of consistent tracing is traditionally used when for the moment t the solution is sought when a complete solution for the moment $(t - \Delta t)$ is known, where Δt is a step of tracing the propagation of elastoplastic deformations, within which it can be approximately supposed that the development occurs according to a fairly simple load trajectory. In this case, the relation between the end increments of the tensor of deformations $\Delta\varepsilon_{ij}$ and the tensor of stresses σ_{ij} according to [9], it can be written in the form:

$$\Delta\varepsilon_{ij} = \psi(\sigma_{ij}-\delta_{ij}\sigma) + \delta_{ij}(K\sigma) - b_{ij}\,, \tag{14}$$

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

$$\begin{gathered} \psi = \frac{1}{2G}, \text{ if } f < 0, \\ \psi > \frac{1}{2G}, \text{ if } f = 0, \\ \text{state } f > 0 \text{ is inadmissible,} \end{gathered} \tag{15}$$

b_{ij} is the tensor function of additional deformations, which is determined by an increase in $\Delta\varphi$ and the known results of the previous stage of tracing:

$$\begin{gathered} b_{ij} = \left[\frac{\sigma_{ij}-\delta_{ij}\sigma}{2G} + \delta_{ij}(K\sigma)\right]_{t-\Delta t} + \delta_{ij}\Delta\varphi \\ (i,j = x,y,z). \end{gathered} \tag{16}$$

Flow conditions in the form (11) include significant physical nonlinearity in the function of the material state ψ. In order to realize this type of physical nonlinearity, iterative processes are usually used. As a result, at each iteration, a physically nonlinear problem passes into a linear type of problem of elasticity theory with a variable shear modulus, which is equal to $1/2\psi$ and additional deformations b_{ij}. To solve such a linearized problem, numerical methods are used.

DEVELOPMENT OF MATHEMATICAL MODEL OF RELAXATION AND REDISTRIBUTION OF RESIDUAL STRESSES IN CWJ DURING HEAT TREATMENT

Welded joints of critical structures are subjected to postweld heat treatment. According to the requirements of standard documentation [11], after welding composite welded joints of structural elements in NPP equipment are subjected to heat treatment applying a high tempering mode.

According to the item 13.18 [8] (for replacement [11]), producing welded joints of parts with steels of pearlite class or high-chromium steels with parts of austenite class steels by austenitic filler materials, are not subjected to heat treatment except for the cases, when it is specified by drawings and/or TPD. In addition, according to the item 13.14 [12], the temperature of tempering welded joints of parts of steels of different grades, for which a different tempering temperature is provided, is specified by TPD. Based on the abovementioned, heat treatment modes were set in accordance with the requirements [6].

In the mathematical modeling of the process of postweld heat treatment of CWJ (cover of RV), the feature of the developed model for determining the nonstationary temperature field was a convective heat transfer on the surfaces due to a gradual heating of the environment (air) in the furnace, holding and a subsequent rather slow cooling in the furnace and then in air. Nonstationary boundary conditions corresponded to a uniform increase in the ambient temperature in the process of heating and to a decrease in temperature to 20 °C during cooling.

The diagram of heat treatment mode, namely, changes in the ambient temperature T_{out} in the process of high tempering of RV cover in the furnace during heating at a rate of 30 °C/h, holding during 9 h and cooling at a rate of 30 °C/h is shown in Figure 4.

Initial and boundary conditions of the boundary value problem of determining temperature distributions in CWJ during heat treatment in time *t*:

$$T_{out}(0) = 20\ °C,\ T(0) = 20\ °C,$$
$$q = -h(T_{out}(t) - T),\ T_{out}(t) = 30\ °C/h \cdot t,$$
$$T_{out}^{max} = 650\ °C.$$

The heat transfer coefficient from the surfaces of CWJ elements during convective heat exchange with the environment in the furnace and in the air was taken equal to $h = 30$ W/m^2 °C in the conditions of a natural convection and constant heating and cooling throughout the whole temperature range. A radiant heat exchange in the developed model was not modelled separately, its contribution was taken into account in some increase in the value of the heat transfer coefficient.

A long-term process of heating welded structural elements to a holding temperature of 650 °C causes processes of a high-temperature creep in the material, which leads to relaxation of residual stresses in the area of welded joints.

In the developed model, the problem of determining SSS during heat treatment was solved in a visco-elastoplastic formulation [9]:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} + \varepsilon_{ij}^{cr}\ \ (i, j = x, y, z)\,, \tag{17}$$

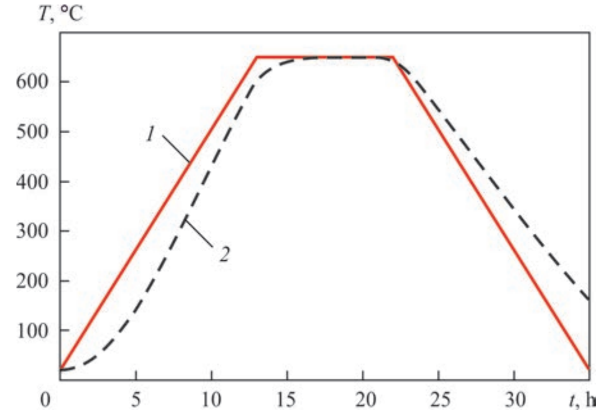

Figure 4. Diagram of changing temperature of CWJ material in the process of heat treatment using a high tempering mode at T = 650 °C: *1* — heat treatment mode; *2* — calculated temperature

where the rate of creep deformations was determined by the Bailey–Norton's law [13]:

$$\dot{\varepsilon}_{eq}^{cr} = A \cdot \sigma_{eq}^{n}\,. \tag{18}$$

For austenitic 08Kh18N10T steel at a temperature of 700 °C (973 K), while determining the rate of deformations of a temperature creep, the following coefficients can be accepted: $A = 6.948 \cdot 10^{-14}$ (MPa^{-n}·h^{-1}) $n = 6.22$ [14].

RESULTS OF MATHEMATICAL MODELING OF TEMPERATURE DISTRIBUTIONS AND MICROSTRUCTURAL PHASE TRANSFORMATIONS

The results of modeling microstructural transformations in CWJ metal during welding ($T_{heating}$ = 100 °C) and a subsequent cooling showed (Figure 5) the presence of local formation of hardened structures in HAZ of the nozzle metal (steel 20) and in the base material of the cover (steel 15Kh2NMF). Figure 6 presents diagrams of changes in the microstructural phase state at the characteristic point of HAZ of the base material of the cover, where the maximum residual martensite content was obtained, depending on heating temperature. The use of preheating during CWJ welding at the level $T_{heating}$ = 200 °C allows reducing the relative con-

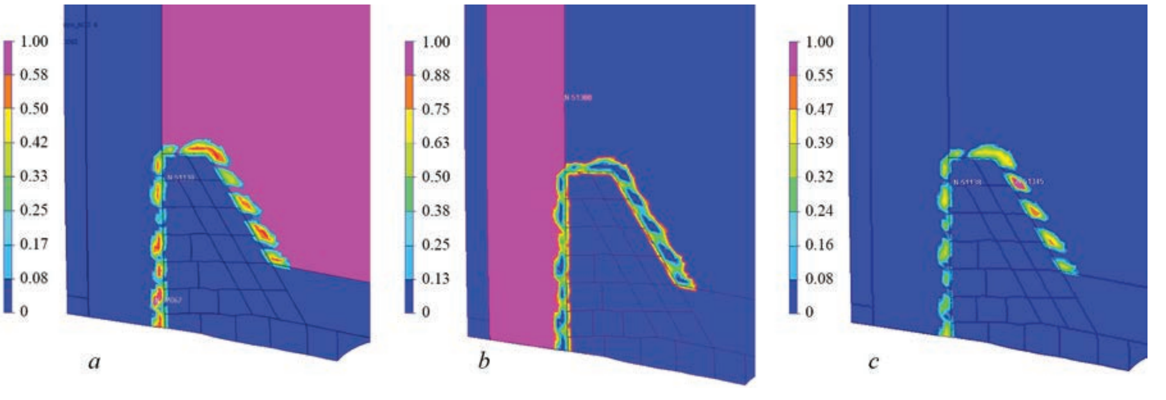

Figure 5. Results of modeling residual microstructural composition in the CWJ zone at $T_{preheating}$ = 100 °C: *a* — bainite; *b* — ferrite-pearlite; *c* — martensite

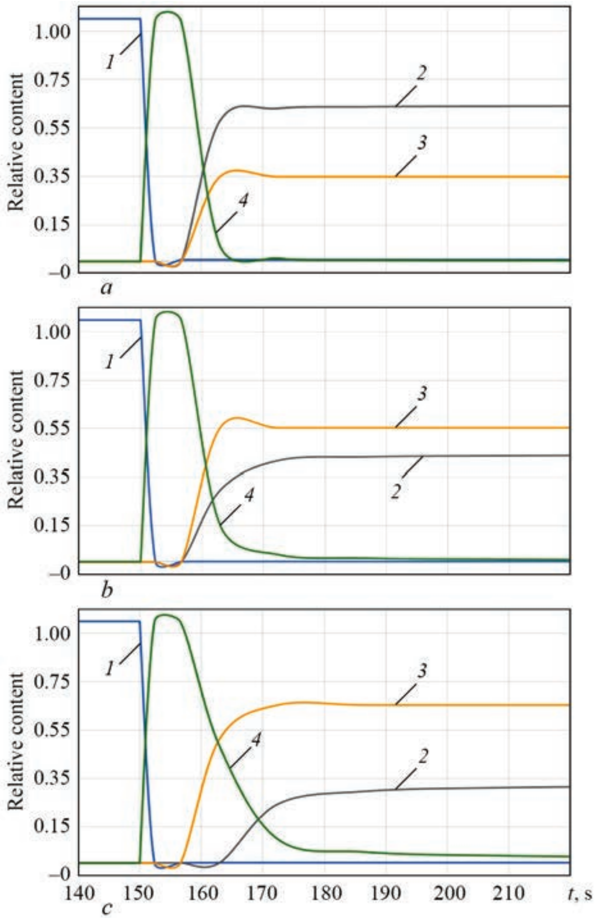

Figure 6. Kinetics of microstructural phase transformations at the characteristic point of HAZ of the base material of the cover (15Kh2NMFA steel) for different preheating temperatures: *a* — without preheating; *b* — $T_{preheating}$ = 100 °C; *c* — $T_{preheating}$) = = 200 °C; *1* — ferrite; *2* — martensite; *3* — bainite; *4* — austenite

tent of martensite in HAZ from 65 to 30 % as compared to welding without preheating.

RESULTS OF MATHEMATICAL MODELING OF RESIDUAL STRESSES AFTER WELDING AND AFTER HEAT TREATMENT

Figure 7 presents the distribution of residual stresses after welding CWJ at the temperature of preliminary and accompanying heating $T_{heating}$ = 100 °C and a subsequent cooling to T = 20 °C. The radial (relative to the nozzle axis) component in the area of the welded joint (Figure 7, *a*) is characterized mainly by tensile residual stresses of up to 200 MPa and local areas of maximum tensile stresses of up to 400 MPa in the base material of the cover adjacent to the austenitic weld metal and in the material of the nozzle, in the upper part, adjacent to the weld metal. The axial (in the direction of the nozzle axis) residual stresses (Figure 7, *b*) have a low level in the austenitic material of the deposit and the weld, and in the base material of the cover and the nozzle, the zones of compressive and tensile stresses of up to 400 MPa were formed. The highest tensile stresses (up to 700 MPa) were determined for the circular component of residual stresses (Figure 7, *c*) in the area of the base material of the cover, which is adjacent to the austenitic weld metal.

Thus, after welding CWJ, rather high residual tensile stresses were obtained, which can negatively affect the strength of the reactor cover during further operation. Therefore, the use of technological operation of postweld heat treatment is absolutely justified. After modeling of welding, modeling of a general

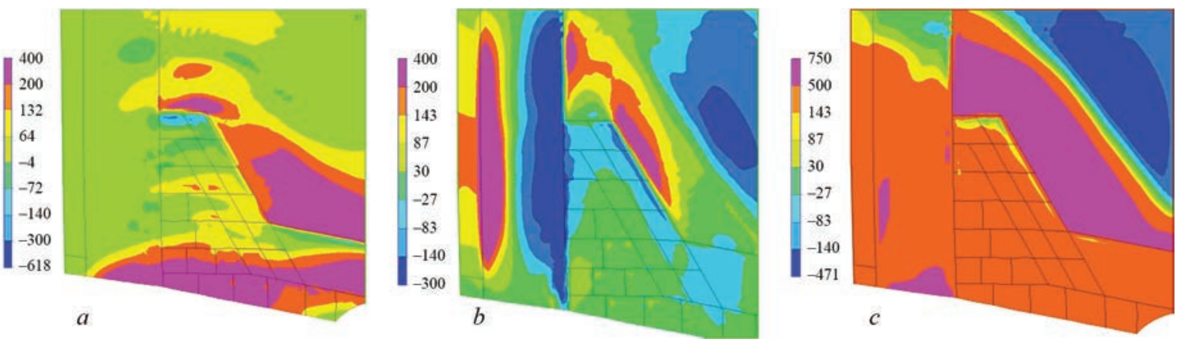

Figure 7. Residual stresses in CWJ after welding at $T_{heating}$ = 100 °C: *a* — radial; *b* — axial; *c* — circular

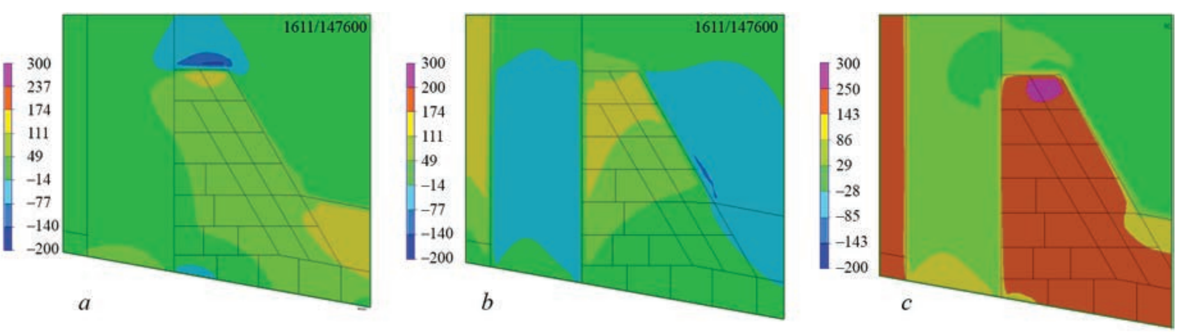

Figure 8. Residual stresses in CWJ after welding ($T_{heating}$ = 100 °C) and heat treatment (T = 650 °C, $t_{holding}$ = 15 h): *a* — radial; *b* — axial; *c* — circular

heat treatment was performed according to the mode of high tempering at a temperature of 650 °C with a holding time of 15 h (see Figure 4). The results of the calculation are shown in Figure 8.

ANALYSIS OF EFFECT OF HEATING TEMPERATURE AND HEAT TREATMENT MODE ON RESIDUAL STRESSES

In order to determine the effect of heating temperature during welding and heat treatment mode on residual stresses of a composite (dissimilar) welded joint of the WWER-1000 reactor vessel cover in representative cross-sections (Figure 9), the diagrams of stress distribution were constructed over the thickness of the welded joint (Figures 10–12).

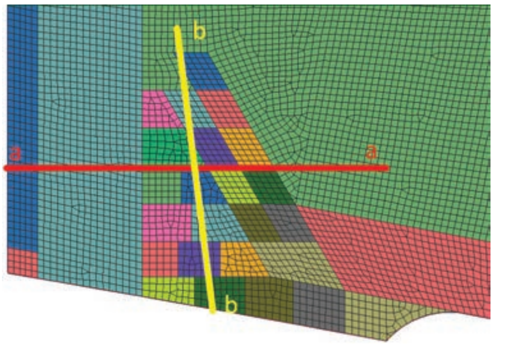

Figure 9. Cross-sections for determination of stresses

The effect of heating temperature during welding on distribution of residual stresses is insignificant, in the selected cross-section of the welded joint over the

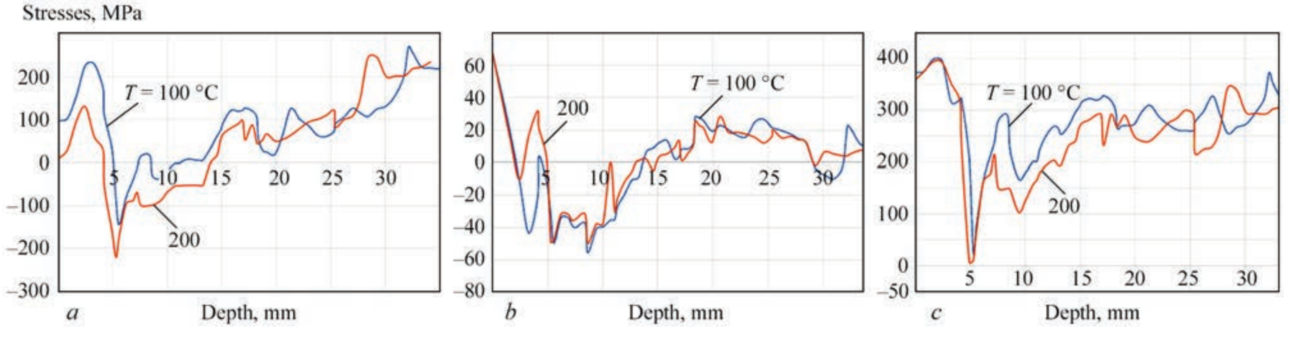

Figure 10. Effect of heating temperature during welding on distribution of residual stresses over the depth of the weld (cross-section *b–b* Figure 9): *a* — radial; *b* — axial; *c* — circular

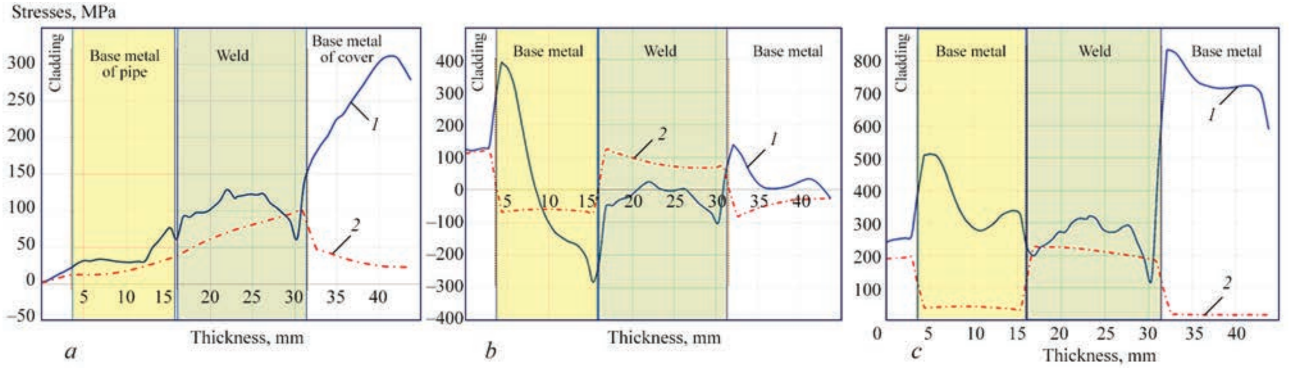

Figure 11. Effect of heat treatment (T = 650 °C) on distribution of residual stresses across the width of the weld (cross-section *a–a* Figure 9): *a* — radial; *b* — axial; *c* — circular; *1* — before heat treatment; *2* — after heat treatment

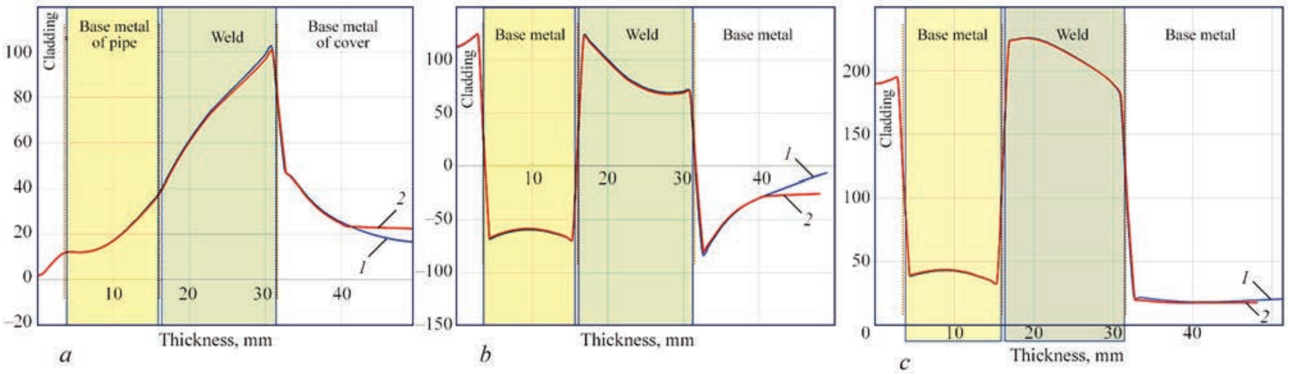

Figure 12. Effect of holding time during heat treatment (T = 650 °C) on distribution of residual stresses across the width of the weld (cross-section *a–a* Figure 9): *a* — radial; *b* — axial; *c* — circular; *1* — 15 h; *2* — 9

depth of the weld (Figure 10), maximum residual tensile stresses in the radial direction noticeably decrease (from 220 to 120 MPa) with an increase in heating temperature, other components (in axial and circular directions) are almost unchanged.

The effect of heat treatment ($T = 650$ °C) on distribution of residual stresses is quite significant. Radial stresses are noticeably reduced, especially in the area of the base material of the cover, from 300 to 30 MPa (Figure 11, *a*). The axial component of residual stresses in the area of the pipe and cover material decreases, and in the austenitic weld material it increases to 100 MPa (Figure 11, *b*), which is associated with the difference in the coefficients of thermal expansion of different CWJ materials.

The effect of holding time ($t_{\text{holding}} = 15$ h) during heat treatment ($T = 650$ °C) on distribution of residual stresses is also insignificant (Figure 12). Relaxation of residual welding stresses largely occurs during the first hour of holding at the maximum temperature, and distribution of residual stresses after heat treatment is determined mainly by the difference in thermophysical properties of different joining materials.

CONCLUSIONS

1. Analysis of the results of mathematical modeling of SSS in the composite welded joint of the WWER-1000 reactor vessel cover with the CSS nozzle showed that the distribution of residual stresses after welding has a complex nature with high tensile stresses in the zones of ferritic-pearlitic materials, inherent in joints of dissimilar materials (base material of the cover of 15Kh2NMFA steel and the nozzle of steel 20).

2. It was determined that in welding CWJ without heating, the residual content of hardened structures in the HAZ metal of the nozzle (steel 20) and in the base material of the cover (steel 15Kh2NMF) can reach 65 %. The use of preliminary (accompanying) heating can significantly reduce the relative content of martensite in the base material of the cover and the nozzle at the boundary interface of fusion with the austenitic weld material.

3. Postweld heat treatment at a high tempering mode ($T = 650$ °C) reduces the level of residual stresses, but due to a significant difference in the coefficients of thermal expansion of dissimilar joining materials, new rather high residual tensile stresses are formed in the areas of austenitic deposited materials.

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CONFLICT OF INTEREST

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