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MATHEMATICAL MODELING OF RESIDUAL STRESS RELAXATION DURING PERFORMANCE OF POSTWELD HEAT TREATMENT

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ABSTRACT

In order to lower the level of residual stresses, welded joints of a number of structural steels are subjected to general or local postweld heat treatment by the high-temperature tempering mode. Mathematical modeling methods are widely used, alongside the experimental investigation methods, to satisfy the continuously growing requirements to welded joint quality and to optimize the welding technology. Mathematical modeling of the process of welded joint heat treatment is often performed using a simplified creep function by Norton–Bailey law at a fixed soaking temperature, but here the processes of ductile deformation taking place during slow prolonged heating and cooling, are ignored. The effectiveness of application of different models of temperature creep for mathematical modeling of the processes of relaxation of residual stresses in welded joints was studied in this work with the purpose of developing recommendations for their application for various characteristic cases of postweld heat treatment. Comparison of the results of modeling the process of stress relaxation performed on a number of examples, showed that the simplified creep function at short-term soaking during general furnace treatment can give an error compared to a more general creep model. Modeling of the local heat treatment technology revealed that the complex geometry of the component and poor choice of the heating element arrangement may lead to negative consequences, namely formation of new high residual stresses. Proper modeling of the processes of relaxation and redistribution of residual stresses in welded joints and structures as a result of general (furnace) or local post-weld heat treatment may optimize the process of furnace heat treatment and improve the quality and fatigue life of the welded structures.

KEYWORDS: postweld heat treatment, high-temperature annealing, residual welding stresses, stress relaxation, mathematical modeling, creep function

INTRODUCTION

Provision of increasing industrial requirements to welded joint quality from point of view of their reliability is related with corresponding fundamental investigations of the main physical processes which determine quality of mentioned above products after manufacture and some period of operation. Methods of mathematical modeling and current information technologies have found wide application alongside the experimental investigations.

Welded joints of a series of structural steels (ferrite-pearlite, bainite, martensite classes), in particular, welded joints of large thicknesses are subjected to general (in furnace) or local heat treatment (HT) by high-temperature tempering mode to decrease the level of residual welding stresses [1, 2]. This technological operation is particularly necessary in the case when a structure is going to be operated at low temperatures, cyclic loads, in aggressive medium, i.e. when a role of residual stresses in provision of structural integrity can become very important [3, 4].

The modes of postweld HT are not always optimum. In series of cases of application of local or general tempering of welded joints the residual stresses during heating can partially relax, but after that in cooling the new ones form if heating or cooling of joint material was nonuniform [5, 6] or thermal-physical properties of materials do not match as in the case of dissimilar joints and deposits [7, 8]. Therefore, development of the proper modes of postweld HT technology, in particular, using mathematical modeling methods, can allow significant decrease of material expenses related with provision of safe operation of critical equipment. Thus, the aim of the work is investigation of efficiency of application of different models of temperature creep for mathematical modeling of processes of relaxation of residual stresses in welded joints and development of recommendations on their application for different typical cases of postweld HT.

METHODOLOGY

On the strain plasticity theory there is dependence between deformation and stresses for elastic-plastic body. Strain intensity for an isotropic body equals a sum of plastic and elastic strains intensities [9, 10]. Plastic strain, which increases with time at constant stress, is called a creep strain (ε^c). Graphic presentation of dependence of plastic strain on time t of tests in case of effect of constant stresses and temperature is called a creep curve (Figure 1) [9].

In the general case of thermomechanical loading a nature and value of deformations of product is determined using the data on elasticity modulus, Poisson's coefficient, material yield point depending on temperature as well as rate of creep strain of material at set temperature depending on values of loads (stresses).

In welded elements subjected to HT the total effect of high temperatures and inner residual stresses provoke appearance and development of elastic-plastic strains. For mathematical model used in modeling of elastic-plastic deformation of material of welded joint it is assumed that increment of tensor of strain $d\varepsilon_{ij}$ in a random point (x, y, z) in moment of time t is presented in form of sum [3]:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{c}, \qquad (1)$$

where $d\varepsilon_{ij}^{e}$ is the elastic component of strain tensor; $d\varepsilon_{ij}^{p}$ is the component from instant plasticity and $d\varepsilon_{ij}^{c}$ is the component of creep strain (diffusion plasticity). A function of material creep corresponding to Norton–Bailey [11] law is often used for modeling of a process of heat treatment of welded joints. It is a power dependence between the stress intensity σ_i and creep rate at fixed soaking temperature of HT:

$$\frac{d\varepsilon^{c}}{dt} = A\sigma_i^{n}, \qquad (2)$$

or in modified shape with additional effect of soaking time t [12]

$$\frac{d\varepsilon^{c}}{dt} = A\sigma_i^{n} t^{m}, \qquad (3)$$

where A, n, m are the coefficients which determine experimentally the characteristics of material at set temperature $T = \text{const}$.

Provided model is developed for prediction of accumulation of creep strain depending on time on stage I of non-steady-state creep and stage II of steady-state creep (Figure 1) that corresponds to the conditions of deformation during postweld HT. However, application of such creep model in modeling of the processes of relaxation of residual stresses does not consider creep processes taking place at temperatures lower than temperature of soaking in HT, i.e. in heating and cooling of material or in the zones of welded joint where temperature of material during local HT is lower than the set soaking temperature.

Let's consider a mathematical model of Arrhenius creep that considers accumulation of creep strain in a wide range of material temperature [13].

$$\frac{d}{dt} = B\sigma_i^{n} \exp\left(\frac{Q\ \ k}{T(K)}\right) = B\sigma_i^{n} \exp\left(\frac{G}{T(^\circ\mathrm{C}) + 273}\right), \qquad (4)$$

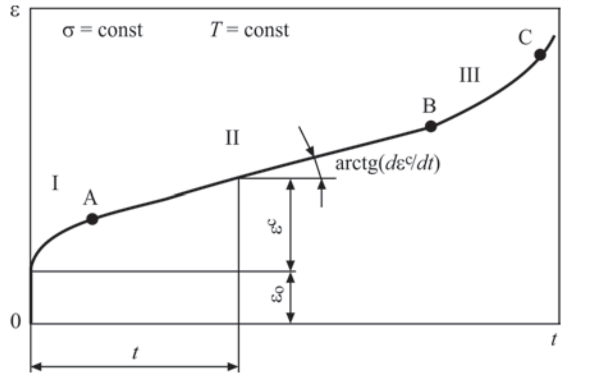

Figure 1. Creep curve: I — stage of non-steady-state creep; II — stage of steady-state creep; III — stage of failure; ε_0 is the instant initial deformation

where Q is the energy of creep activation; k is the Boltzmann constant; T (K) is the absolute temperature by Kelvin scale; T (°C) is the temperature in Celsius degrees; B, G, n are the constants.

Provided creep model (4) at elevated temperatures is relatively general, it allows tracing deformation processes in HT. This model is effective in modeling of the processes of relaxation of residual stresses at local or furnace HT of welded structures in short-term soaking when uniform heating until the set soaking temperature is not provided on a volume of welded structure or assembly.

According to the provided models of high-temperature creep and known models of elastic-plastic deformation of material [3] it is possible to develop the mathematical models of joint development of elastic strains, instant plasticity and creep for high-temperature heating of elements as a result of postweld HT. Mostly in this case it is possible to use the current developments for solution of the problems of theory of elasticity and building mechanics based on wide application of finite elements method. A method of successive tracing allows taking into account the kinetics of development of stressed state not only from successively made welding passes, but also from operation of postweld HT. Reliability of the results obtained by described procedure to significant extent depends on output data on thermophysical and mechanical properties of material of tested object and parameters of heat and power effect.

Let's consider a series of examples of application of mathematical models of creep (1) and (4) in modeling of typical cases of postweld HT.

EXAMPLE No. 1. LONGITUDINAL WELDED JOINT OF CYLINDER SHELL OF IN-VESSEL CAVITY OF WWER-1000 REACTOR

In-vessel cavity (IVC) of nuclear reactor WWER-1000 is a welded cylinder shell from austenite steel 08Kh18N10T of outer diameter 3610 mm and wall thickness 60 mm, that contains longitudinal and circumferential butt joints which can be produced by multipass submerged-arc welding with following HT for relaxation of residual stresses.

Distributions of the residual welding stresses [14] for longitudinal multipass welded joint (10–12 passes) of cylinder IVC shell were obtained using the mathematical modeling method. After welding a procedure of general (furnace) HT of welded joint was modeled for mode: $T = 650$ °C, duration of soaking 10 h. For steel 08Kh18N10T at temperature $T = 650$ °C the values of A and n coefficients in Norton–Bailey equation (2) were take as following [15]:

$$A = 6.07307\cdot10^{-14}\ \text{MPa}^{-n}/\text{h},\ n = 4.8351.$$

For this mathematical model parameters A and n were taken equal for the base and weld metal. Figure 2 shows a diagram of creep function for steel 08Kh18N10T at temperature $T = 650$ °C and taken parameters A and n. It demonstrates that at high values of stress intensity (more than 100 MPa) formation of creep strains takes place with sufficiently high rate (0.0003–0.01 h^{-1}). At low stresses the processes of their relaxation dramatically slow down.

Welded structure of IVC can be subjected to general furnace HT. Such HT can be modeled based on application of two fundamentally different approaches for determination of temperature distributions. First approach is simplified to the maximum and assumes that during heating, soaking and cooling the temperature of material is forcibly set equal to equilibrium on whole volume of welded assembly. Second approach takes into account possible nonuniformity of temperature distribution on structure thickness due to convective heating from surface.

The results of calculation of stress-strain state of IVC after welding and HT showed that the maximum axial stresses σ_{zz}, which equaled 200 MPa after welding, reduced to 48 MPa after HT. The maximum circumferential stresses $\sigma_{\beta\beta}$ as a result of HT reduced from 174 to 50 MPa, radial σ_{rr} from 63 to 10 MPa.

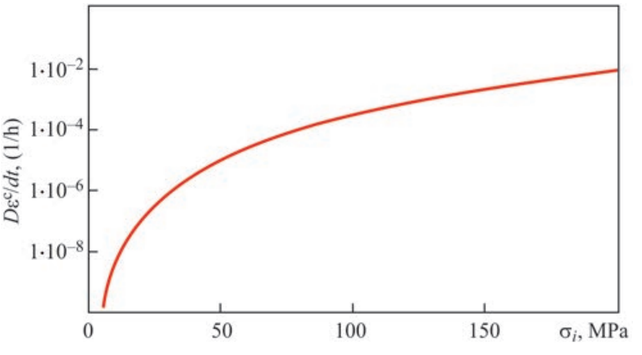

Figure 2. Creep function for 08Kh18N10T steel at $T = 650$ °C temperature

Figure 3 shows the change of temperature of air in furnace volume, which correspond to the set parameters of HT as well as calculation results of kinetics of maximum temperature of heating of welded joint metal due to convective heat exchange and results of kinetics of relaxation of residual stresses σ_{zz} at different rates of heating and cooling. Coefficient of convective heat exchange on surface of welded joint with air in furnace volume was taken in a range $\alpha = (1.5$–

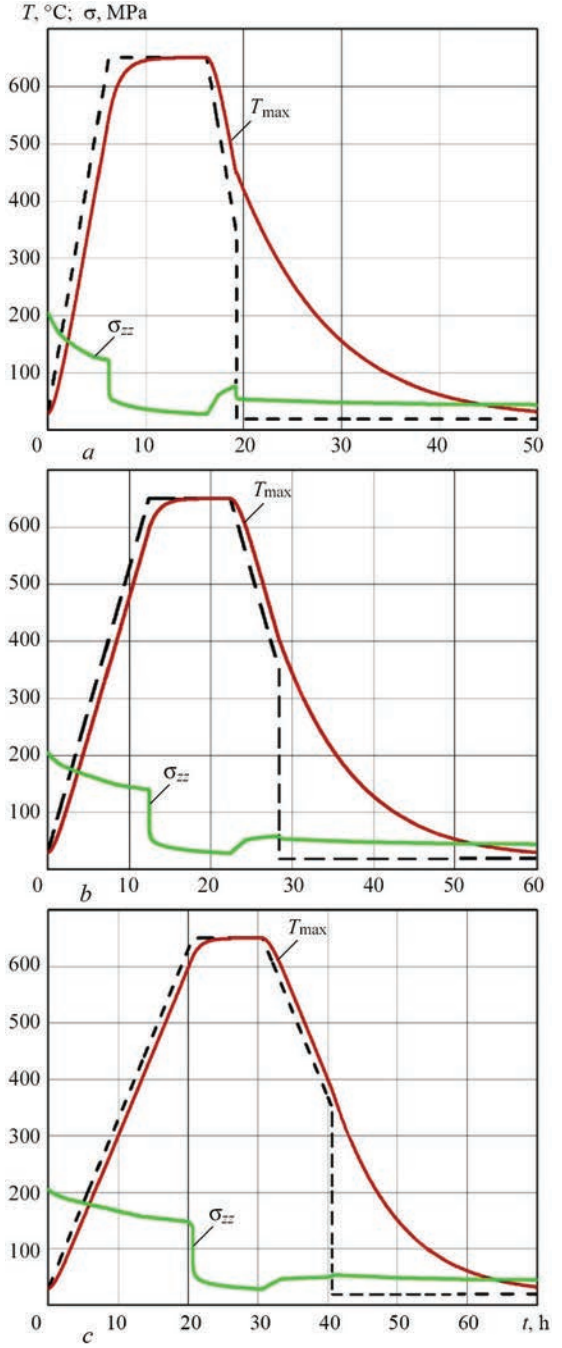

Figure 3. Change of air temperature in furnace (dashed line) and calculation results of kinetics of maximum temperature of heating of metal of welded joint and relaxation of maximum residual stresses (axial component σ_{zz}) at different rates of heating and cooling: *a* — 100 deg/h; *b* — 50; *c* — 30

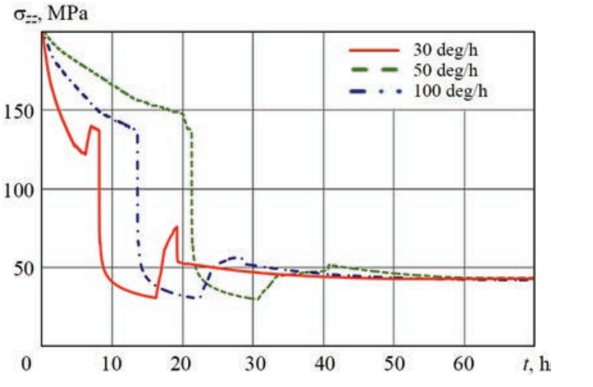

Figure 4. Kinetics of relaxation of maximum residual stresses σ_{zz} in HT in welded joint zone with different rates of heating and cooling (100, 50, 30 deg/h), soaking time 10 h, T_{max} = 650 °C, for model of convective heating in furnace

$3.0)\cdot10^{-4}$ J/(mm^2·s·deg) depending on temperature of heated metal.

Heating promotes relaxation of residual stresses due to instant plasticity and after heating to 650 °C during soaking this takes place due to the process of temperature creep. It should be noted that the developed simplified model uses an assumption that the creep process starts at soaking temperature. Thus, the creep process at 650 °C has sufficiently intensive start. Substantial stress relaxation takes place in course of first hour of soaking after that creep rate noticeably decreases. After cooling the level of residual stresses slightly rises due to increase of temperature dependence of material yield limit.

At considered variants of heating and cooling rates the welded joint of 60 mm thickness has uniform enough heating on thickness and differs by delay value at reaching the soaking temperature 650 °C. At sufficiently long period of soaking (10 h) that was taken in calculation the results by efficiency of relaxation of residual stresses for different heating and cooling rates virtually have no difference (Figure 4). Maximum σ_{zz}, which after welding were at 200 MPa level, reduce to 45–48 MPa after HT.

Figure 5 presents the dependence of efficiency of relaxation of residual welding stresses σ_{zz} on soaking time. The results of calculation in HT for a variant of convective heating in a furnace at heating rate up to 650 °C and cooling 100 deg/h show that soaking time is a very important parameter.

The difference in relaxation of residual stresses at 10 and 5 hours soaking is not large: residual stresses σ_{zz} decrease to 45 and 50 MPa, respectively. Efficiency of HT decreases at shorter soaking of 650 °C. At three h soaking σ_{zz} deceased to 60 MPa, for 2 hto 86 MPa.

Figure 6 provides a comparison of the results of modeling of relaxation of residual stresses σ_{zz} in HT in the case of forced uniform heating (approach 1) with the results of modeling of HT by heating due

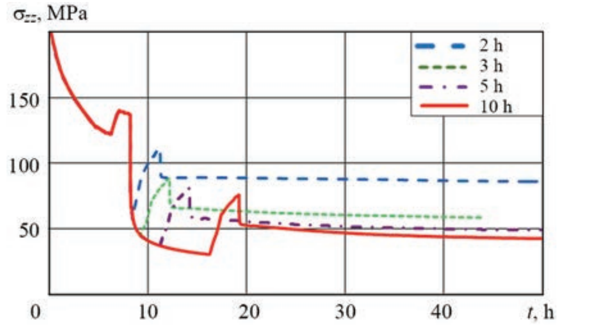

Figure 5. Kinetics of relaxation of maximum residual stresses σ_{zz} in HT in welded joint zone on soaking time (2, 3, 5, 10 h, T_{max} = 650 °C), at heating and cooling rate 100 deg/h for model of convective heating in furnace

to convection (approach 2) for soaking during 2 and 10 h at 650 °C, heating and cooling rate is 100 deg/h.

At sufficiently long-term soaking, when welded joint is completely heated on thickness, the results of numerical prediction of relaxation of residual stresses by simplified approach 1 are close to more accurate approach 2, which takes into account a level of heating on thickness and delay of heating to soaking temperature. Thus, at 10 h soaking the results of relaxation of the maximum residual stresses σ_{zz} (Figure 6), obtained by approaches 1 and 2, give 45 and 43 MPa, respectively. For short-term soaking (2 h) the simplified approach 1 gives significant error, namely 59 MPa against 86 MPa using more accurate approach 2, therefore, an error makes approximately 30 %.

EXAMPLE No. 2. CIRCUMFERENTIAL WELDED JOINT OF PIPELINE FROM INCREASED STRENGTH STEEL OF PEARLITE CLASS

Welded joints of pipelines of power equipment are as a rule subjected to postweld HT. For example, welded joints of reactor coolant pipe (RCP) Du850 from steel 10GN2MFA (pearlite class) are made using manual or automatic welding. A weld root is made manually using argon-arc welding with filler wire 08G2S of

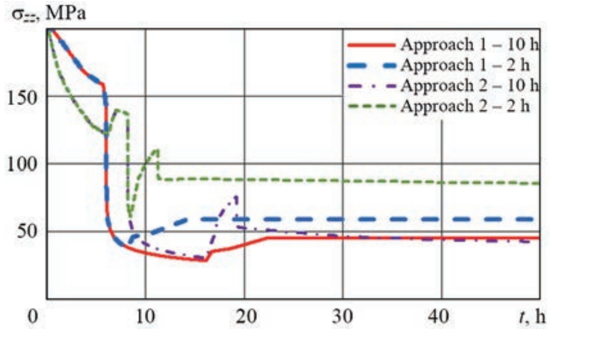

Figure 6. Comparison of conditions of forced uniform heating (approach 1) with heating due to convection (approach 2) in HT by the results of modeling of relaxation of maximum residual welding stresses σ_{zz} for different time of soaking 2 and 10 h, T_{max} = = 650 °C, heating and cooling rate 100 deg/h

Table 1. Results of calculation of coefficients of creep functions (2) and (4) using experimental data [3]

T, °C	A, 1/(MPa^n·h)	B, 1/(MPa^n·h)	G, K
	$n = 6$	$n = 6$	$n = 6$
550	$0.43\cdot10^{-17}$	exp(41.28)	– 66394
600	$1.13\cdot10^{-15}$		
650	$1.73\cdot10^{-14}$		
700	$3.77\cdot10^{-12}$		

2–3 mm diameter, height of root pass is 6–8 mm. Filling of main part of the weld is carried out by manual welding with electrodes PT-30 of 4 mm diameter and wire Sv10GN1MA of 2 mm diameter is used at automatic welding. Welding is performed with preliminary and concurrent heating to 150 °C.

For determination of residual welding stresses there was carried out the mathematical modeling in 2D axially symmetric problem statement of the non-stationary heat conductivity and thermoplastic deformation in welding heating of a circumferential multi-pass welded joint (112 passes) of a cylinder shell with inner diameter D_{inner} = 850 mm, thickness δ = 60 mm, mode of arc welding run I_w = 250 A, U_w = 11.5 V, ν_w = = 5.5 mm/s, Q_1 = 520 J/mm, coefficient of thermal efficiency equals 0.8.

There was obtained a sufficiently high level of circumferential component of residual stresses $\sigma_{\beta\beta}$ up to 400–500 MPa, i.e. to a material yield limit and in a local zone of final welding passes the maximum calculation circumferential stresses reach almost 690 MPa.

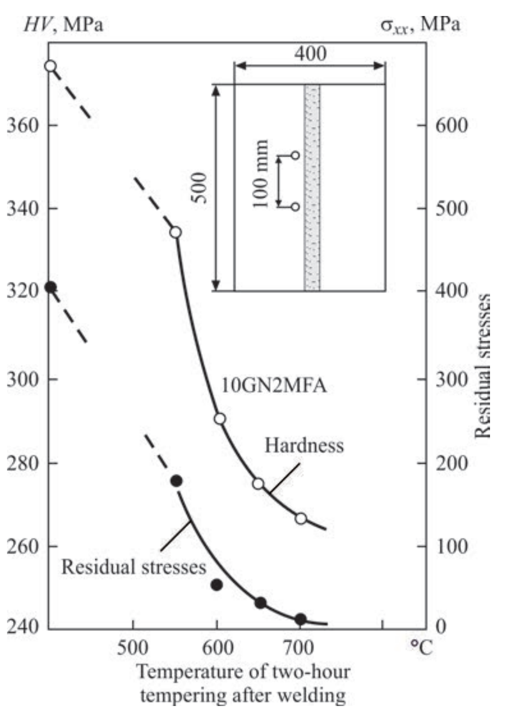

Figure 7. Effect of temperature of two-hour tempering after welding on level of residual stresses and hardness in zone of welded joint of steel 10GN2MFA [16]

High-temperature tempering at 650 °C temperature is used after welding for the purpose of relaxation of residual stresses. Time of soaking at set temperature is 6–7 h, cooling to 200 °C in a furnace at set rate of cooling to 100 deg/h then free cooling to temperature 20 °C on air.

Two creep functions were used in modeling of the process of relaxation of residual stresses in HT for determination of possible difference of results and provision of necessary prediction accuracy. First — simplified (2), does not depend on temperature and acts only at reaching soaking temperature in HT. Second (4) — more general and depends on material temperature starting from temperature of 550°C and higher.

Coefficients of creep function for base material of RCP pipeline (steel 10GN2MFA) are determined based on processing of experimental data. Figure 7 provides the data of work [3] corresponding to the level of relaxation of tensile residual longitudinal stresses for soaking period 2 h HT after welding of plates of steel 10GN2MFA depending on tempering temperature T = 550–700 °C. Table provides the results of calculation of constants A, B, G, n of creep functions (2) and (4) using these experimental data.

Simplified creep function can be obtained only based on data for soaking temperature T = 650 °C in HT and present in form (2)

$$\text{at } n = 6,\ A = 1.73\cdot10^{-14}\ 1/(\text{MPa}^n\cdot\text{h}).$$

Respectively the creep function in general depending on material temperature starting from 550 °C and higher can be approximated by typical dependence (4) with corresponding coefficients B, G, n from the Table 1.

Obtained results of modeling of residual stress relaxation in a zone of circumferential welded joint of RCP Du850 after HT and complete cooling to 20 °C indicate on sufficiently high level of efficiency of relaxation of residual stresses at set parameters (T = 650 °C, soaking time 7 h). The level of maximum residual tensile stresses, namely circumferential component $\sigma_{\beta\beta}$ and axial σ_{zz} one does not exceed 30–40 MPa, compression stresses on inner surface are somewhat higher from — 70 to — 80 MPa.

Comparison of accuracy of modeling of the process of stress relaxation using simplified creep function based on Norton–Bailey law for fixed soaking temperature and more general creep function are given on Figure 8. The comparison was carried out for efficiency of relaxation of residual circumferential stresses $\sigma_{\beta\beta}$ in a zone of butt welded joint of RCP Du850 in HT depending on selection of creep

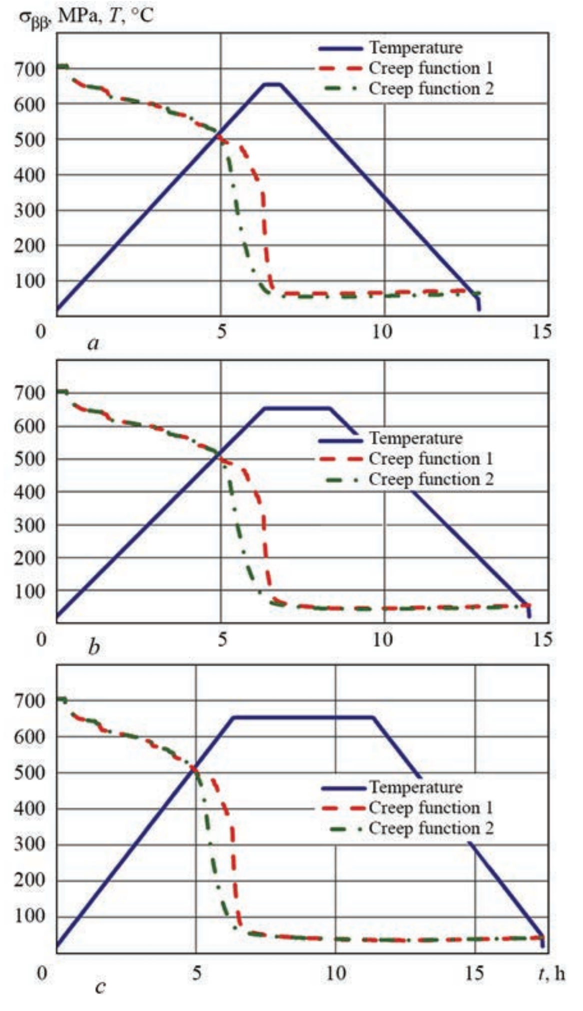

Figure 8. Dependence of efficiency of relaxation of residual stresses $\sigma_{\beta\beta}$ (circumferential component) in zone of butt welded joint of RCP Du850 in HT on selection of creep function and time of soaking (T = 650 °C): *a* — 0.5; *b* — 2 and *c* — 5 h

function and time of soaking at T = 650 °C (0.5; 2 and 5 h), heating and cooling rate 100 deg/h. It can be noted that depending on creep function there is a change of stress relaxation kinetics, namely at more general creep function the processes of relaxation due to creep start earlier at T = 550 °C temperature, but at soaking the creep curves approach and almost match. The maximum residual stresses $\sigma_{\beta\beta}$ decrease from 710 to 50 MPa in a welded joint zone. Only in the case of very short soaking (0.5 h) stress relaxation by simplified model does not have time to take place and difference in values of residual stresses after HT becomes noticeable — 50 and 65 MPa. Thus, the simplified creep function in the cases of very short soaking can give significant error in the results of modeling of relaxation of residual stresses relatively to the more general creep function which considers dependence of the creep process on temperature of heating and cooling stage. In the considered case the relative error made approximately 30 %.

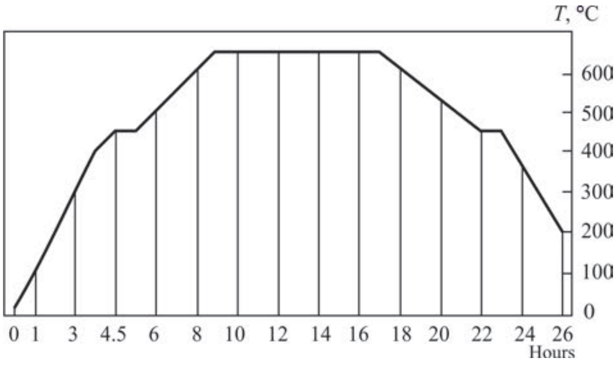

Figure 9. Diagram of HT by high-temperature tempering mode

EXAMPLE No. 3. LOCAL HT OF WELDED JOINT No. 111 OF COLLECTOR TO NOZZLE Du1200 OF PGV-1000 STEAM GENERATOR

Nozzle Du1200 of steam generator and collector is made from pearlite class steel 10GN2MFA. A weld is carried out manually or automatically, weld root is made manually using argon-arc welding with filler wire Sv08G2S, height of root pass is 6–8 mm. Filling of the main part of weld is carried manually using TsU or UONI-13/55 electrodes of 4 or 5 mm diameter and Sv08GSMT and Sv10GN1MA wires of 2 mm diameter and FTs-16 or AN-17 fluxes are used for automatic welding. Operations of intermediate and final high-temperature tempering (Figure 9) are carried out by circular heaters (Figure 10) for the purpose of relaxation of residual stresses related with assembly welding or local repair of separate defects by a scheme of multilayer filling of corresponding grooving of welded joint No. 111.

Additional heat sources that provide local HT of the welded assembly can be set by corresponding heat flow through heating surface or change of surface temperature in a heating zone, if the latter is performed by a set program as indicated for high-temperature tempering mode.

There was carried out a mathematical modeling of a problem of nonstationary heat conductivity and thermoplastic deformation in welding heating during

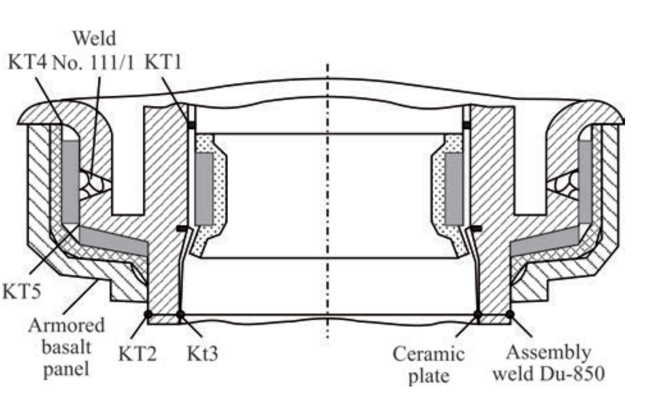

Figure 10. Scheme of installation of heaters and heat-insulating materials in sections of welded joint No. 111 in postweld HT (CP1 = CP5 — control points)

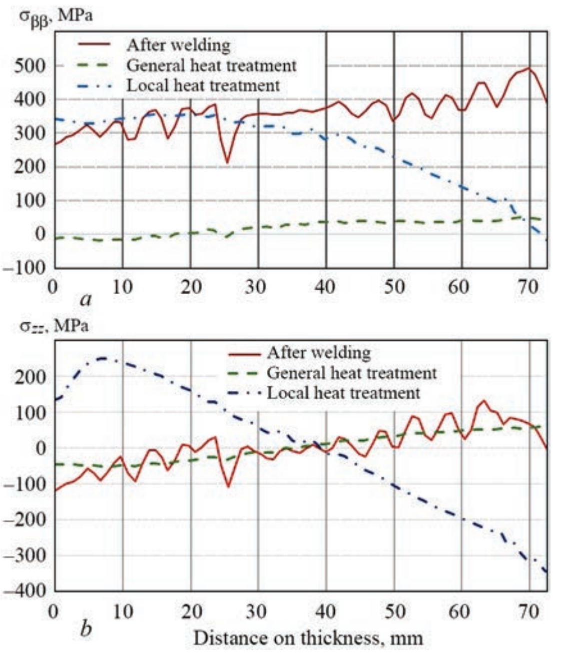

Figure 11. Distribution of residual welding stresses of axial σ_{zz} (*a*) and circumferential $\sigma_{\beta\beta}$ (*b*) on thickness of welded joint No. 111 after welding and after general and local HT

performance of all (up to 100) passes of groove filling of welded joint No. 111 and further complete cooling. As a result there were obtained the distributions of components of residual stresses which are rather nonuniform on welded joint thickness. Tensile circumferential stresses $\sigma_{\beta\beta}$ (to 650 MPa) have the highest level. Axial residual stresses σ_{zz} are compression ones (to — 170 MPa) on inner surface of the joint and tensile ones on outer (to 350 MPa). Radial component σ_{rr} has tensile stresses to 200 MPa.

From point of view of failure resistance of welded joint No. 111 by stress-corrosion cracking mechanism the distributions of circumferential and axial residual stresses on the joint inner surface are particularly important. After assembly welding rather high circumferential residual tensile stresses (to 300 MPa) and axial compression stresses were determined in the indicated zone. Taking into account geometry complexity of the assembly of welded joint No. 111, technological operation of local postweld HT can not only decrease the level, but also promote formation of new residual stresses.

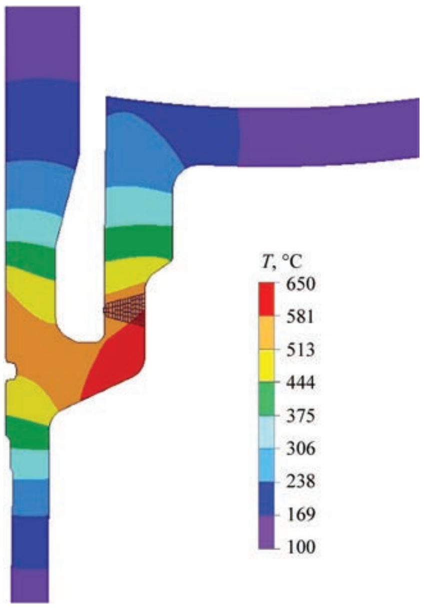

Figure 12. Distribution of temperature in process of soaking in local postweld HT

During performance of this investigation, similar to previous examples, there were used two approaches for modeling of temperature distributions during postweld HT. Thus, the first simplified approach corresponds to the conditions of general furnace HT, when whole welded joint is forcedly uniformly heated according to set HT mode. The second approach corresponds to the real conditions of heat treatment, i.e. in a zone of heater installation (Figure 10) the surface temperature changes in time *t* (beginning from start of heater operation) by diagram of HT mode (Figure 9). The rest of assembly surface has an insulation or heat exchange with environment by Newton–Richmann law.

Performance of general HT of welded joint No. 111, modeling of which is provided by uniform heating (approach 1) of the assembly to soaking temperature 650 °C results at soaking time 8 h to significant relaxation of residual stresses, namely the level of all components of residual stresses reduced from 100 MPa and lower (Figure 11).

In modeling of relaxation and redistribution of residual stresses in welded joint No. 111 the obtained results are different in essence when performing local HT by means of application of heat flows from the heater from assembly surface (approach 2). First of all, heating using locally located heaters does not provide uniformity of distribution of temperature in the zone of welded joint in the process of soaking due to complex assembly geometry (Figure 12). As a result, significant nonuniform heating promotes formation of new residual stresses, distribution and level of which dramatically differ from residual stresses after welding (Figure 11).

After local HT the circumferential welding residual stresses $\sigma_{\beta\beta}$ on the inner joint surface virtually do not change and reach the level of 350 MPa and sufficiently high after welding circumferential residual tensile stresses at 400 MPa level reduce to 0–100 MPa (Figure 11, *a*) on the outer surface. Axial residual stresses σ_{zz} on inner surface which after welding were the compression stresses at — 100 MPa level become the tensile stresses and reach the level of 200–300 MPa after local HT and on outer surface have compression values to — 300 MPa (Figure 11, *b*).

Thus, the local high-temperature tempering with nonuniform distribution of temperature in a zone of welded joint under conditions of sufficiently rigid assembly of welded joint No. 111 results in some decrease of circumferential residual stresses on the weld outer surface, however a new zone of high axial tensile stresses is formed on the inner joint surface.

Provided results as for investigation of efficiency of technology of local HT of welded joint No. 111 showed that improper selection of a place for heater positioning in local HT can result in negative consequences, namely formation of the new residual tensile stresses in the dangerous zones of welded assembly. Low efficiency of considered technology of postweld HT and probably even its negative effect on integrity of welded joint No. 111 indicate the necessity of optimization of technology of local HT including, in particular, mathematical modeling methods.

CONCLUSIONS

1. In case of general furnace HT of welded structure the heat processes can be modeled based on application of two different approaches. The first, more economical by realization approach assumes that in heating, soaking and cooling the material temperature is set forcedly uniform by welded assembly volume according to given mode of heat treatment. The second one more accurate approach considers the possible nonuniformity of structure temperature distribution as a result of heating and cooling from surface due to convection with ambient air in the furnace.

2. Comparison of the results of modeling of relaxation of residual welding stresses in HT in case of forced uniform heating with the results of HT modeling due to convection showed that in case of long enough soaking in HT, when the welded joint has time for complete heating on thickness, the first approach provides the results on relaxation of residual stresses very close to the second one, which considers the level of heating on thickness and delay of heating to soaking temperature. In case of short soaking time the first approach can give significant error.

3. Modeling of process of HT of welded joints is often based on a simplified function of material creep by Norton–Bailey law as power dependence between stress intensity and creep strain rate at fixed soaking temperature. More general mathematical models of creep, for example, Arrhenius model, can take into account accumulation of creep strain in a wide range of material temperatures and allow tracing the deformation processes not only at soaking temperature, but at lower temperatures of material and can be effective in modeling of the processes of relaxation of residual stresses in local HT of welded structures or in the case of the general furnace heat treatment at short soaking time, when uniform heating to set soaking temperature is not provided by volume of welded structure or assembly.

4. Comparison of the results on efficiency of relaxation of residual stresses showed that the calculation kinetics of stress relaxation changes depending on creep function. Thus, in the case of more general creep function the relaxation processes start earlier due to creep in heating, however in process of soaking the creep curves by simplified and general models approach and almost match. In case of very short soaking the simplified creep function can provide significant error in the results of modeling of residual stresses relaxation in relation to more general creep function which considers dependence of creep process on temperature on heating and cooling stages. In the considered case of HT of RCP butt welded joint Du850 the relative error made 30 %.

5. Study of efficiency of a technology of local HT of the welded joints showed that complex assembly geometry and improper selection of heaters location can result in negative consequences, namely formation of the new residual tensile stresses in the dangerous zones of welded assembly. It is related with significant inhomogeneity of temperature distribution at local heating of the assembly. It is relevant to carry out optimization of the new technologies of local HT involving mathematical modeling methods in order to increase efficiency of a technology of postweld local HT and elimination of its possible negative effect on integrity of welded joints.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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