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COMPUTER SOFTWARE FOR MODELING A CIRCUMFERENTIAL WELDED JOINT

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ABSTRACT

The specialized software "Girth Weld" is developed by specialists of the PWI and allows for typical cases of welded girth joints of pipelines and cylindrical pressure vessels to predict the mechanical properties of the weld metal and the heat-affected zone (HAZ), residual stresses and distortions, to determine the redistribution of the stress-strain state as a result of postweld heat treatment, operational and test loading, to assess the structure integrity and service life of welded structures with discontinuity defects that are detected by non-destructive testing or are postulated. The use of this software does not require special knowledge in the calculation methods due to the full automation of the processes of creating a mathematical model of a multipass girth welded joint, dividing the area into finite elements, searching for a solution and visualizing the results. At the same time, high accuracy of predictive results is ensured with limited requirements for computer and time resources through the use of modern approaches to modeling physical and chemical processes during welding and effective algorithms for solving nonlinear problems and systems of high-order differential equations.

KEYWORDS: girth welded joint, multipass welding, software, mathematical modeling, finite element method, mechanical properties, residual stresses, distortions, postweld heat treatment, operational loads, defect acceptability

INTRODUCTION

With the development of computer technology, methods for solving problems of thermoviscoplastic analysis and modeling changes in the material of the welded joint during welding heating, computational simulation and mathematical modeling of welding processes are widely used in industry. However, the issue of accessibility of such an approach for a user with limited access to commercial FEM software packages such as SYSWELD, SIMUFACT, ABAQUS, ANSYS, etc. is relevant. To solve this problem, a problem-oriented specialized software "Girth Weld" was created, which is included in the "Weldprediction" software package, for mathematical modeling of the stress-strain state and mechanical properties in the zone of a butt circumferential (girth) joint produced by multipass arc welding, oriented for engineering and scientific application, which does not require the user to have knowledge in the calculation methods.

The computer program "Girth Weld" allows in the typical cases of circumferential welded joints of pipelines and cylindrical pressure vessels to obtain information on the mechanical properties of the weld metal and the HAZ, residual technological stresses and distortions, to determine the redistribution of the stress-strain state as a result of postweld heat treatment (PWHT), the influence of operational and test loads, and to predict the structural integrity and service life of welded structures with discontinuity defects that are detected by non-destructive testing or are postulated.

The software "Girth Weld" was developed at the PWI. Its implementation is based on many years of experience in mathematical modeling of physical and chemical processes during welding, cladding, PWHT and related technologies, as well as modern achievements in numerical methods, mechanics of deformed bodies and fracture mechanics. At the same time, the developed specialized software has the following advantages:

- high accuracy of predicted results with limited requirements for computer and time resources (personal computer and relatively short calculation time) due to the use of modern approaches to modeling physical and chemical processes in welding [1, 2, 3, 10, 11] and effective algorithms for solving nonlinear problems and systems of high-order differential equations [4, 5];
- reduced labor intensity due to a simple data entry interface and automation of the processes of creating a mathematical model, forming a finite element mesh, finding a solution and visualizing the results;
- accessibility in use, since an engineer or welding technologist can work with the computer program without having special knowledge in the numerical methods for solving mathematical problems.

GENERAL DESCRIPTION AND PURPOSE OF THE COMPUTER PROGRAM

The specialized software "Girth Weld" is a problem-oriented software product for numerical FEM analysis of the technological and physical and mechanical processes during multipass welding of circumferential joints of pipeline elements and cylindrical pressure vessels. The computer program is intended for solving typical tasks of expert assessment of technological strength of critical structures when planning assembly or repair welding and PWHT of girth joints, as well as prediction of short-term and long-term static strength during further operation of the welded structure, taking into account both its residual post-weld state and the acting external operational loads.

The software "Girth Weld" is recommended for use in the energy, transport, aerospace and other industries in the design, optimization of assembly welding and planning of repair work of critical pipeline elements and pressure vessels with circumferential welded joints. This software is also recommended for use in expert assessment of structural integrity and service life of welded structures, taking into account both their predicted state and operating conditions, as well as the discontinuity defects (cracks, nonmetallic inclusions, local thinning, gas pores) detected during technical diagnostics.

The use of specialized software "Girth Weld" allows solving the following problems:

● prediction of the optimal arrangement of weld passes in multipass welding depending on the technical conditions of the process and welding optimization criteria;

● determination of the kinetics of the temperature field during multipass welding of circumferential joints of pipeline elements and cylindrical pressure vessels taking into account the technological parameters of the welding process, geometric features of a design, type and properties of the material depending on the chemical composition and temperature;

● numerical assessment of the specifics of the formation of the penetration zone along the thickness of the structural element;

● prediction of transient and residual properties, as well as microstructural phase composition of the weld metal and the HAZ depending on the process and welding conditions, base and filler materials, and the temperature cycles during welding;

● prediction of the kinetics of the distribution of elastic-plastic strains in the process of multipass welding of the butt circumferential joint until the structural element is completely cooled and of the subsequent operational internal pressure and temperature;

● calculation of the residual distortions of the structure as a result of uneven welding heating by assessing irreversible shrinkage phenomena in the welded joint area;

● numerical assessment of the kinetics of accumulation of plastic strains, which is an important characteristic of the susceptibility of the weld metal to hot cracking.

The user interface of the software "Girth Weld" implements a dialog mode for numerical analysis and provides the following options for displaying on the screen and saving as files or hard copies the following results of numerical experiments:

● optimal calculation schemes for the arrangement of weld passes in the groove of a circumferential joint;

● two-dimensional distributions of calculated values (maximum temperatures, melting zone, stresses, plastic strains, distortions) both in the form of drawings and tables;

● distribution of microstructural phase components and mechanical properties of the material in the weld area taking into account the influence of local heating in the process of multipass welding with given heat input parameters;

● tendency to the formation of cold and hot cracks;

● distortions of the structure after welding, taking into account irreversible welding shrinkage strains;

● relaxation of the residual stresses due to PWHT;

● redistribution of the residual stresses under loading conditions (temperature and internal pressure);

● assessment of fatigue fracture resistance of a circumferential welded joint under cyclic loading conditions;

● probabilistic assessment of the serviceability of a cylindrical structure in the presence of macroscopic defects of weld metal discontinuity.

METHODS OF NUMERICAL AND SOFTWARE IMPLEMENTATION OF COMPUTER PROGRAM ALGORITHMS

Development a mathematical model for simulation of the welding processes depends on the purpose of simulation. For prediction of temperature cycles, microstructure phase volume fractions, distortions and residual stresses in a multipass welded joint, the finite element models of volume heat source and nonisothermal deformation of material associated with von Mises yield stress condition are usually used [1, 2]. Modeling is based on tracking the kinetics of formation and development of plastic strains and stresses in a weldment during heating and cooling of each weld pass. Microstructural phase transformations, which induce volume effects and changes of physical and mechanical properties of material in the weld zone, are taken into account.

In the general form in a cylindrical system of coordinates r, β, z (Figure 1, *a*) for multipass circumferential (girth) welding during motion of the volume heat source center $r_0(t)$, $\beta_0(t)$, $z_0(t)$ in time (Figure 1, *b*) the heat flux equation at point (r, β, z) at time t can be written as follows

$$W(r, \beta, z, t) = \\ = W_0(t) \exp [-K_r(r-r_0)^2 - K_\beta(\beta-\beta_0)^2 - K_z(z-z_0)^2], \quad (1)$$

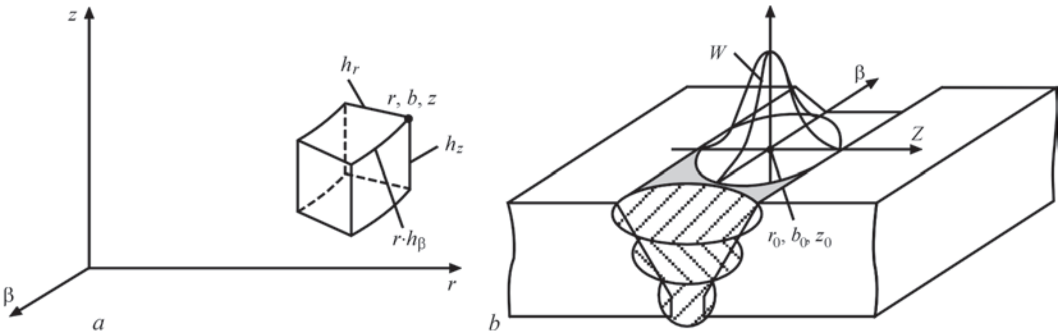

Figure 1. Scheme of finite volume element in cylindrical system of coordinates (*r,* β, *z*) (*a*) and distribution of heating power W(*r,* β, *z, t*) at multipass welding (*b*)

where $W_0(t)$ is the heating power at point (r_0, β_0, z_0); K_r, K_β, K_z are the coefficients of heating power concentration in the directions *r*, β, *z*. Between K_r, K_β, K_z and corresponding dimensions d_r, d_β, d_z of effective heating "spot" there is a relation $K_j \frac{d_j^2}{4} = 3.0$, i.e. $d_j = \frac{3.46}{\sqrt{K_j}}$. $W_0(t)$ can be expressed in terms of the effective heating power $q_{ef}(t)$, by integrating the equation (1) in coordinates *r*, β, *z* within the heated elements of welded joint. For example, if the heat source moves along the surface of the butt welded joint (Figure 1, *b*), then:

$$W_0(t) = \frac{2q_{\text{ef}}(t)\sqrt{K_x \cdot K_y \cdot K_z}}{\pi\sqrt{\pi}}. \tag{2}$$

With quite reasonable values K_r, K_β, K_z accurate results can be obtained for temperature distributions near the fusion zone (FZ) of welded elements, which is important from the point of view of microstructural phase changes, mechanical properties, etc.

The mathematical formulation of the problem of heat propagation in a thermally conducting body for the heat sources *W*(*r*, *z*, β, *t*) and the relevant conditions of heat exchange with the environment with a temperature T_c by Newton's law may be presented in the form:

$$-\lambda\frac{\partial T}{\partial n} = \alpha_T\left(T - T_c\right), \tag{3}$$

where λ is the coefficient of thermal conductivity of the material at a temperature *T*, and α_T is the heat transfer coefficient of the surface are well known. [3]

In accordance with [9] we need to add to conditions (3) the initial condition at time $t = 0$ and the differential equation of heat conduction in the system of coordinates (*r,* β, *z*):

$$\frac{\partial}{\partial r}\left(r\lambda\frac{\partial T}{\partial r}\right) + \frac{\partial}{r\partial\beta}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(r\lambda\frac{\partial T}{\partial z}\right) + \\ +W(r,\beta,z,t) = c\gamma\frac{\partial T}{\partial t}r; \tag{4}$$

$$T(r, \beta, z, t = 0) = T_0, \tag{5}$$

where *c*γ is the volumetric heat capacity of the material at temperature *T*.

Volume effects caused by the change of temperature field are conventionally divided into the temperature effects and effects, caused by microstructural phase transformations [5]. Temperature volume effects at any point

$$\varphi = \alpha(T)(T - T_0), \tag{6}$$

where φ is the function of thermal expansions; α(*T*) is the coefficient of relative thermal elongation; ($T - T_0$) is the temperature range.

When welding steels prone to quenching, the microstructural composition at any point in the FZ and HAZ is determined at time *t* by the values of the relative content of the *j*-th phase $V_j(T, t)$, $j = a$ corresponds to austenite, $j = m$ — martensite, $j = f$ — ferrite, $j = b$ — bainite, $j = fp$ — ferrite-pearlite mixture. In this case $\sum_j V_j(t) \equiv 1$. Volume effects at any point (*r,* β, *z*) due to microstructural phase transformations in the temperature range ($T_0 - T$) [5] are as follows:

$$3\varphi = \frac{\sum V_j(T,t)\gamma_j(T) - \sum V_j(T_0)\gamma_j(T_0)}{\sum V_j(T_0)\gamma_j(T_0)}, \tag{7}$$

where $\gamma_j(T)$ is the the volume of a unit mass of the *j*-th phase at temperature *T*. According to [6] for the structural steels:

$$\begin{aligned} \gamma_m(T) &= 0.12282 + 8.56\cdot 10^{-6}T + \\ &+2.15\cdot 10^{-3}C, (\text{cm}^3/\text{g}); \\ \gamma_a(T) &= 0.12708 + 4.448\cdot 10^{-6}T + \\ &+2.79\cdot 10^{-3}C, (\text{cm}^3/\text{g}); \\ \gamma_{b,fp}(T) &= 0.12708 + \\ &+5.528\cdot 10^{-6}T, (\text{cm}^3/\text{g}). \end{aligned} \tag{8}$$

The yield stress of the finite volume material at temperature *T* considering the microstructural phase changes is calculated as:

$$\sigma_T(T) = \sum \sigma_j(T) V_j(T), \quad (j = a, f, fp, b, m)$$
$$\sigma_T^j(T) = \sigma_T^j(20) \cdot f_j(T), \tag{9}$$

where $\sigma_j(T)$ is the yield stress of the corresponding j-th phase of the microstructure at temperature T; C is the chemical content of carbon (% by weight).

High temperature gradient during welding and a strong irregularity in the distribution of function $\varphi(r, \beta, z, t)$ cause the appearance of both the elastic and inelastic strains. According to [5] a common strain tensor $\varepsilon_{ij}(r, \beta, z, t)$ is a sum of three tensors:

$$\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p + \varepsilon_{ij}^c, \tag{10}$$

where index e is the structural corresponds to the elastic strain; p is the instantaneous strain of plasticity; c is the strain of diffusion plasticity or creep.

Plastic strains are related to the stressed state by the equation of the theory of plastic nonisothermal flow and the associated von Mises yield condition:

$$d\varepsilon_{ij}^p = d\lambda(\sigma_{ij} - \delta_{ij}\sigma), \quad i, j = r, \beta, z, \tag{11}$$

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

$d\lambda = 0$, if $f = \sigma_i^2 - \sigma_T^2(T) < 0$
or $f = 0$ and $df < 0$;
$d\lambda > 0$, if $f = 0$ and $df > 0$;
state $f > 0$ unacceptable,

σ_i is the stress intensity; $\sigma_T(T)$ is the yield stress of the material at temperature T.

For creep strains $_{ij}$, the constraint equation is used in the form:

$$d\varepsilon_{ij}^p = \Omega(T, \sigma_i)(\sigma_{ij} - \delta_{ij}\sigma)dt, \tag{12}$$

where $\Omega(\sigma_i, T)$ is the scalar creep function of the material at temperature T and the stress level, which is determined by the stress intensity σ_i.

For PWHT when it is most important to take into account creep strains, since the stress relaxation process significantly depends on creep, the function $\Omega(\sigma_i, T)$ is rationally chosen on the basis of experiments on deformation of samples from this material at elevated temperatures. The creep function in the general form depending on the material temperature can be approximated by a typical equation [1, 10]:

$$\Omega(T, \sigma_i) = A \cdot \sigma_i^n \cdot \exp\left(\frac{G}{T + 273}\right), \tag{13}$$

where A, G, n are the constants related to material properties.

The presented model of creep at elevated temperatures is quite general and allows to trace deformation processes during PWHT not only during holding at maximum temperature, but also during heating and cooling at temperatures of 550 °C and above, for example, for structural steels. This model can be effective in modeling the relaxation processes of residual stresses during local heat treatment of welded structures or in the case of overall furnace heat treatment for a short holding time, when uniform heating to a given maximum holding temperature is not ensured throughout the volume of the welded joint or structure.

The finite increment of the strain tensor $\Delta\varepsilon_{ij}$ in the time range from $(t - \Delta t)$ to t, where Δt is the step of tracking, is small enough:

$$\Delta\varepsilon_{ij} = \psi\left(\sigma_{ij} - \delta_{ij}\sigma\right) + \delta_{ij}\left(K\sigma + \varphi\right) - b_{ij},$$
$$\left(i, j = r, \hat{a}, z\right);$$
$$\psi = \frac{1}{2G} + \Delta\lambda + \Delta t \cdot \Omega\left(T, \sigma_i\right); \tag{14}$$
$$b_{ij} = \left[\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}\left(K\sigma\right)\right]_{t-\Delta y} - \delta_{ij}\Delta\varphi.$$

where σ_{ij} is the stress tensor; σ is the average pressure; δ_{ij} is the unit tensor; bulk modulus $K = \frac{1-2\nu}{E}$; shear modulus $G = \frac{E}{2(1+\nu)}$; E is the Young's modulus; ν is the Poisson's ratio.

The equation (14) contains the function ψ, which is determined by the plastic flow condition (11) and the development of creep strains (12). This function significantly depends on the initial solution for the moment t and its determination requires certain approaches. The simplest approach is based on the use of the solution for the moment $(t - \Delta t)$. By reducing the step Δt, it is possible to significantly reduce the errors associated with the risk of obtaining unacceptable states (11), however, during welding heating, such a risk is very significant, therefore approaches based on the construction of appropriate iterative processes are used to determine the physical nonlinearity associated with $\Delta\lambda$ and $\Omega(T, \sigma_i)$.

The following iterative process has been well tested in practice:

$$\psi^{(n+1)} = \left[\frac{1}{2G} + \Delta t \cdot \Omega\left(T, \sigma_i^{(n-1)}\right)\right](1-p) + p\psi^{(n)},$$
$$\text{if } \sigma_i^{(n)} - \sigma_T\left(T, \sigma_i^{(n)}\right) < -m;$$
$$\psi^{(n+1)} = \psi^{(n)}, \text{if } -m < \sigma_i^{(n)} - \sigma_T\left(T, \sigma_i^{(n)}\right) < m; \tag{15}$$
$$\psi^{(n+1)} = \psi^{(n)} \frac{\sigma_i^{(n)}}{\sigma_T\left(T, \sigma_i^{(n)}\right)}, \text{if } \sigma_i^{(n)} - \sigma_T\left(T, \sigma_i^{(n)}\right) > m.$$

Process (15) is stopped if:

$$\left|\psi^{(n+1)}/\psi^{(n)} - 1\right| < \delta, \tag{16}$$

where n, $n + 1$ are the iteration numbers, $0 \le p < 1$, $m << \sigma_T\left(T, \sigma_i^{(n)}\right)$, $\delta \le 1$ are the iterative process parameters.

After the linearization procedure the structure of the equation of continuity (14) formally corresponds to the equation of continuity of the theory of elasticity with variable parameters of elasticity (ψ instead of $1/2G$) and additional strains b_{ij}, the value of which is known according to the solution in the previous step of tracking ($t - \Delta t$) and the temperature distributions at moments t and ($t - \Delta t$).

Since in most typical cases of welding and operation of pipeline elements and cylindrical pressure vessels, the distribution of stresses and strains is characterized by a slight change in the circumferential direction (along the weld), in order to reduce the time of numerical investigation and the requirements for the power of computing resources, the numerical schemes in the program code are implemented in a 2D axisymmetric formulation. To develop 2D FE model the assumption of a fast moving welding source and 'plain strains' hypothesis are used.

The software includes a database of input data on the physical and mechanical properties of typical steels and aluminum alloys used for the production of pipeline elements and pressure vessels, which simplifies the procedure for performing calculations and reduces the error of the results of numerical analysis due to the incompleteness of the reference information available to the user. Similarly, the geometry of the welded butt joint can be both determined from a set of available pre-installed options used for structural elements of critical purpose, and entered by the user in the presence of the necessary information regarding a specific design solution.

USER INTERFACE

The user interface of the software is designed for welding engineers who do not have special knowledge in mathematical methods. All tasks for developing a finite element model of a multipass girth welded joint are fully automated. All calculation results can be presented in both the graphical and tabular form. It is possible to copy information from any window to a graphic file, clipboard or to a printer. To save all input data and calculation results, there is a function for saving a variant. Figures 2, 4 show the computer program windows: the main window (Figure 2) for entering the geometrical parameters of the cylindrical structure and circumferential welded joint, the base and filler materials, welding conditions and operational load. Also shown are the PWHT simulation windows (Figure 3) and the module for probabilistic assessment of crack-like defect acceptability in the zone of the welded joint (Figure 4).

THE MAIN LIMITATIONS OF THE COMPUTER PROGRAM:

- metallic materials: steel, light alloys, titanium and nickel alloys;
- geometrical parameters of the cylindrical structure: diameter D = 2–10000 mm; wall thickness H = 1.0–20.0 mm, $H < D/2$; length $2L$ = 60–2000 mm, $L > 30H$;
- preparation of the edges of the circumferential welded joint is one-sided (from the outside);
- the number of welding passes in the circumferential joint is from 1 to 200;
- the material of the structure is considered as a macrocontinuous isotropic elastic-plastic medium capable of strain hardening;

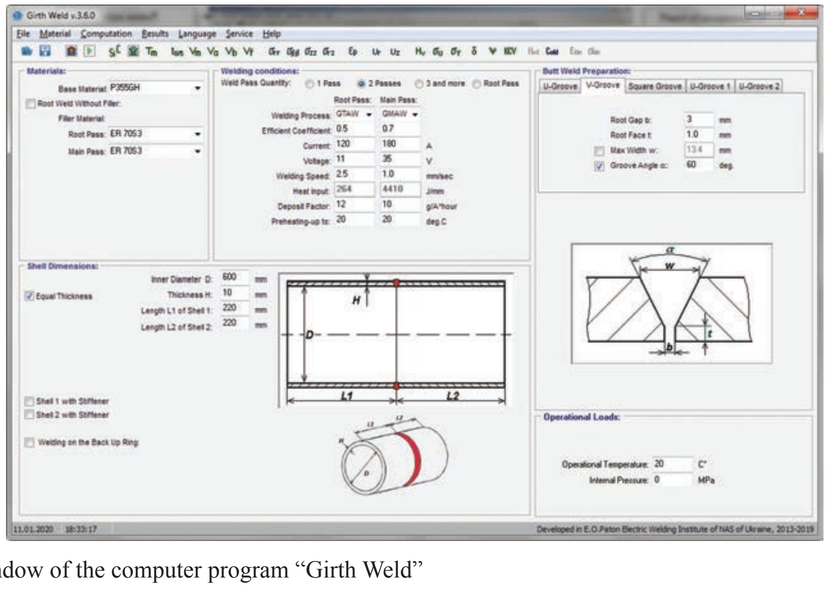

Figure 2. The main window of the computer program "Girth Weld"

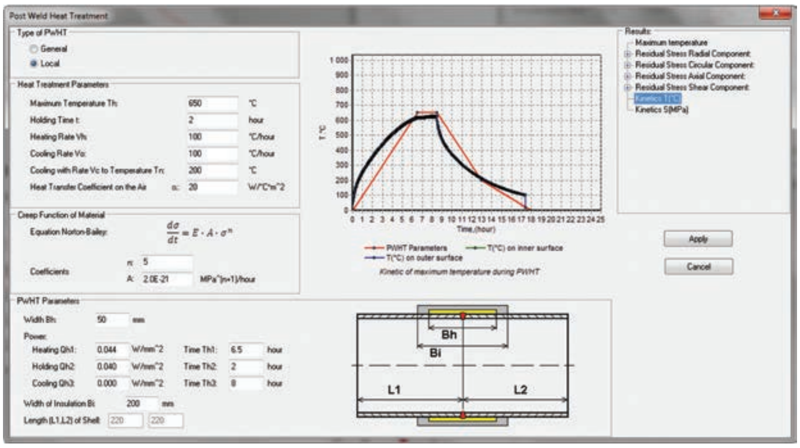

Figure 3. The window of PWHT simulation

- maximum temperatures during welding do not exceed the boiling point of the metal of the structure;
- the structures are not subject to the influence of cryogenic temperatures during operation;
- operational loads: internal pressure from 0 to $P < (0.5\sigma_T 2H/D)$, for example, if $H = 5$ mm, $D = 400$ mm, $\sigma_T = 170$ MPa, then $P < 2.125$ MPa.
- defect acceptability is determined by the conditions of static or quasi-static strength, while the application of assessment methods corresponds to the framework of application of specific criteria used in accordance with the relevant regulatory documents.

Cracks: semi-elliptical in the axial and circumferential directions, on the outer and inner surfaces. Crack dimensions: depth $a_0 < H$, length $2c_0$, $a_0/c_0 < 0.7$. Crack growth occurs by the fatigue mechanism.

Pores: diameter $d_0 < 1.0$ mm, depth r_0: $d_0/2 < r_0 <$ $< H - d_0/2$.

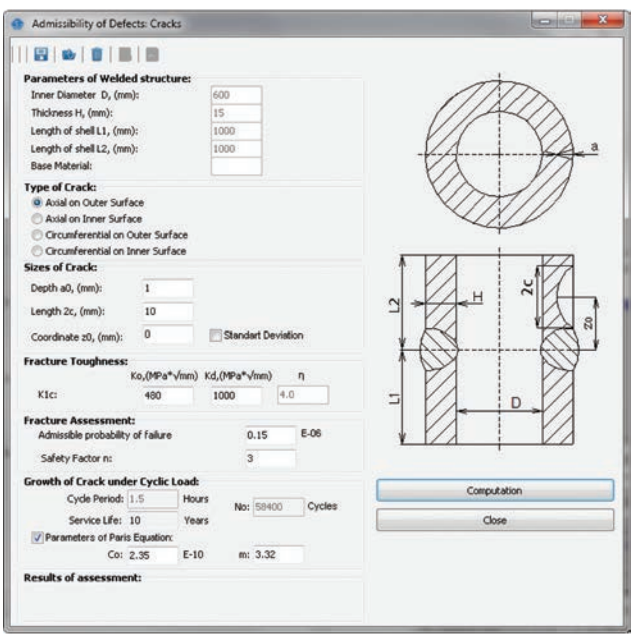

Figure 4. The window of the module for probabilistic assessment of the crack-like defect acceptability

Wall thinning [11]: on the outer and inner surfaces. Thinning dimensions: depth a_0: $a_0 < H/2$, length $2s_0$: $2s_0 < L/2$. Thinning increase occurs by corrosion mechanism.

THE ERROR ENSURED IN THE RANGE OF ACCEPTABLE PARAMETERS OF NUMERICAL ANALYSIS

The adequacy of the developed models and their software implementation is ensured and confirmed both by the validation and verification procedures carried out, and by the experience of successful implementation and use of calculation methods and software in optimizing the industrial technologies of welding circumferential joints of critical structures and confirming their operability and service life by domestic and foreign enterprises of the energy, machine-building, transport, and aerospace industries. As shown by comparison of the results of calculations using the computer program “Girth Weld” with experimental measurements, the error of numerical analysis generally does not exceed 10–15 %.

VERIFICATION OF SIMULATION RESULTS FOR WELDING OF A DISSIMILAR GIRTH PIPELINE JOINT

Residual stresses are important for considering the problems of cracking and fracture of welded struc-

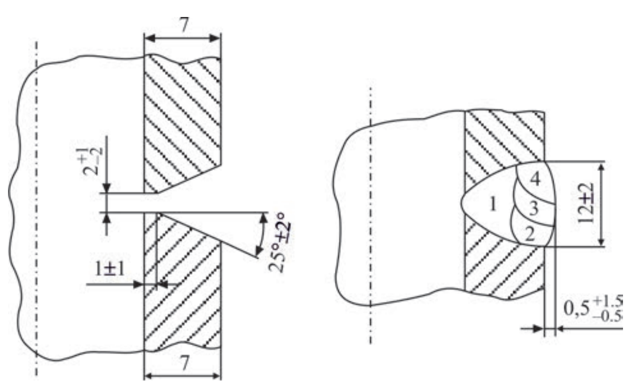

Figure 5. Preparation of edges of U-type for the welded pipe joint (SMAW) (*a*), arrangement of the weld passes (*b*)

Table 1. Mechanical and thermophysical properties of the materials

T, °C	*E*, MPa	α, (10*e*–6·1/K	λ, J/cm·s·deg	*C*, $J/cm^3\cdot deg$
Martensitic steel 12 % Cr				
20	215404	12.1	0.18	3.53
100	211697	12.1	0.19	3.75
200	205591	12.4	0.20	4.02
300	197750	12.8	0.22	4.32
400	188169	13.1	0.23	4.68
500	177028	13.5	0.24	5.15
600	164580	13.9	0.25	6.09
700	154030	13.0	0.27	6.00
800	131900	12.1	0.29	5.20
900	120604	11.1	0.31	4.64
1000	111687	12.5	0.32	4.75
1100	102607	13.6	0.33	4.90
1400	34172	17.5	0.36	9.50
1500	0	24.1	0.35	5.64
Austenitic steel 0.12C–Cr18Ni10T				
20	196531	19	0.146	3.54
100	191369	19	0.156	3.70
200	184280	19	0.168	3.86
300	176922	20	0.180	3.99
400	169296	20	0.193	4.11
500	161416	20	0.205	4.24
600	153303	20	0.218	8.32
700	141463	21	0.236	4.73
800	133320	21	0.249	4.56
900	125217	21	0.262	4.77
1000	116988	22	0.275	4.80
1100	108545	22	0.288	4.96
1200	99881	22	0.301	5.13
1300	88793	23	0.316	5.87
1400	2102	26	0.319	27.00
1500	0	30	0.319	5.64

Table 1. Cont.

T, °C	*E*, MPa	α, (10*e*–6·1/K	λ, J/cm·s·deg	*C*, $J/cm^3\cdot deg$
Welding material E–0.11C–Cr16Ni25Mo6Mn2N (austenitic)				
20	203437	18	0.119	3.58
100	198385	18	0.130	3.73
200	191493	18	0.145	3.87
300	184422	18	0.160	3.99
400	177172	19	0.175	4.10
500	169742	19	0.190	4.21
600	162130	19	0.205	4.41
700	153178	19	0.220	4.57
800	144799	20	0.235	4.84
900	135985	20	0.249	5.05
1000	126625	21	0.263	5.32
1100	117816	21	0.277	4.88
1200	109326	21	0.292	4.99
1300	100669	21	0.307	5.10
1400	74695	22	0.320	11.56
1500	0	28	0.319	5.74

tures and can be simulated for the welding process. The development of new heat-resistant steels for the power industry, where pipes joined by circumferential welding are often used, requires studying the influence of welding processes and residual stresses on the safe and reliable operation of power plants.

Finite element modeling of the multipass SMAW process (manual arc stick welding) was performed for a girth weld of a pipe with an outer diameter of 42 mm and a wall thickness of 7 mm made of 12 % Cr martensitic steel and dissimilar materials (austenitic or pearlitic steel). Such welded joints are used for pipes in the superheater of a boiler in thermal power plants.

The purpose of mathematical modeling is to predict temperature fields and kinetics of the stress-strain state during multipass welding, taking into account the martensitic steel class, the choice of welding materials, welding conditions, preheating temperature, as well as determining the residual stressed state after welding and PWHT.

After preliminary experiments with testing of the welding technology, more acceptable welding parameters were selected, with filling of the weld groove in 4 passes (Figure 5). For a dissimilar welded joint (steel 12 % Cr + austenitic steel 0.12C–Cr18Ni10T), electrodes of the E–0.11C–Cr16Ni25Mo6Mn2N type with a diameter of 3.0 mm were selected with the following parameters: for 1 pass $I = 75–85$ A, $U = 24$ V, $V \approx 1.8$ mm/s, for 2–4 passes $I = 85–90$ A, $U = 24$ V, $V \approx 2.6$ mm/s. Welding procedure was elaborated by V. Skulskyi, A. Gavrik, M. Nimko in PWI.

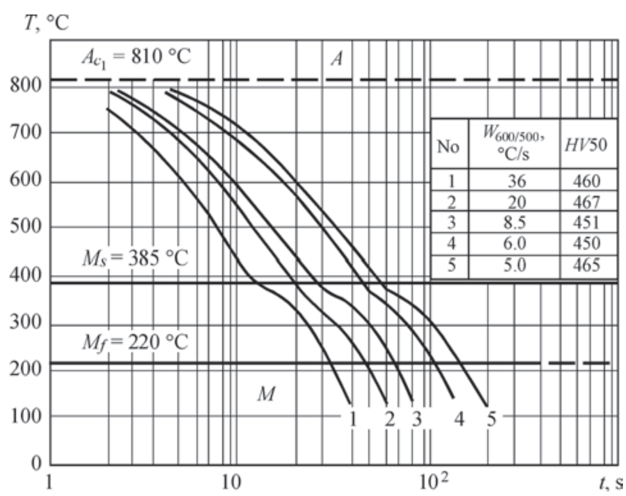

Figure 6. CCT diagram for steel X10CrMoVNb91 [7]

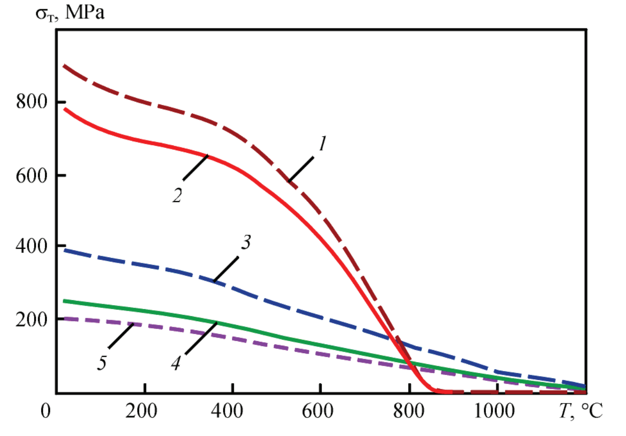

Figure 7. Yield stress versus temperature and microstructure: *1* — V_m = 1.0 martensite Thermanit MTS616; *2* — V_m = 1.0 martensite of 12 Cr steel; *3* — V_a =1.0 austenite of 12 Cr steel; *4* — austenitic filler E–0.11C–Cr16Ni25Mo6Mn2N; *5* — austenitic base material 0.12C–Cr18Ni10T

The chemical composition, mechanical and thermal properties of the base and filler materials are presented in Table 1.

Considering the martensitic class of high-chromium (12 %) steel, the following conditions for the phase transformation of the HAZ microstructure are accepted:

$$\text{if } T > A_c, \text{ then } V_a = 1.0\ ,\ V_m = 0$$

$$\text{if } T < A_c \text{ and } \left(\frac{\partial T}{\partial t} < 0\right), \text{ then } V_j = V_j(T, t), j = a,m$$

$$V_m(T) = 1 - \exp\left(3\frac{T_s^{(m)} - T}{T_s^{(m)} - T_e^{(m)}}\right);$$
$$V_a(T) = 1 - V_m(T), \quad \sum_j V_j(t) \equiv 1, \qquad (17)$$

where $j = a$ corresponds to austenite, $j = m$ — to martensite, $V_j(T, t)$ — is determined from the CCT diagram for the steel with the corresponding chemical composition. An example of CCT diagram of austenite decomposition for steel X10CrMoVNb91 is given in Figure 6 [7]. Dependences of yield stress of base and welding materials on temperature and microstructure are presented in Figure 7.

Comparison of the results of numerical calculations using 2D and 3D models (Figure 8) for butt welding of pipes made of dissimilar materials (12 % Cr steel + austenitic steel) shows a good agreement.

The results in Figure 9 demonstrate a rather close distribution of maximum temperatures during welding of all four passes using 2D and 3D models. In the diagrams, the red color corresponds to the shape of the FZ, the size of the HAZ is limited by the isotherm of 800–850 °C and reaches approximately 1.5–2–5 mm, the depth of the weld metal penetration into the base material is approximately 1 mm. The FZ, the depth of the weld penetration and the temperature range in the HAZ correspond to general expectations.

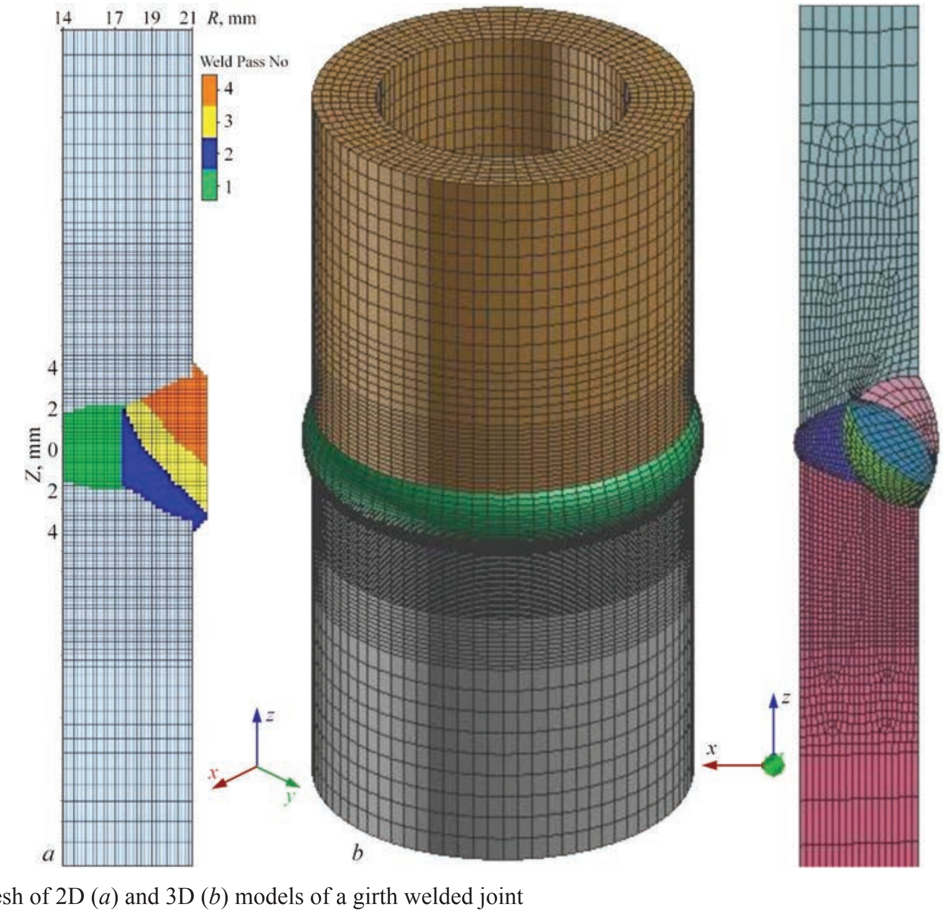

Figure 8. FE mesh of 2D (*a*) and 3D (*b*) models of a girth welded joint

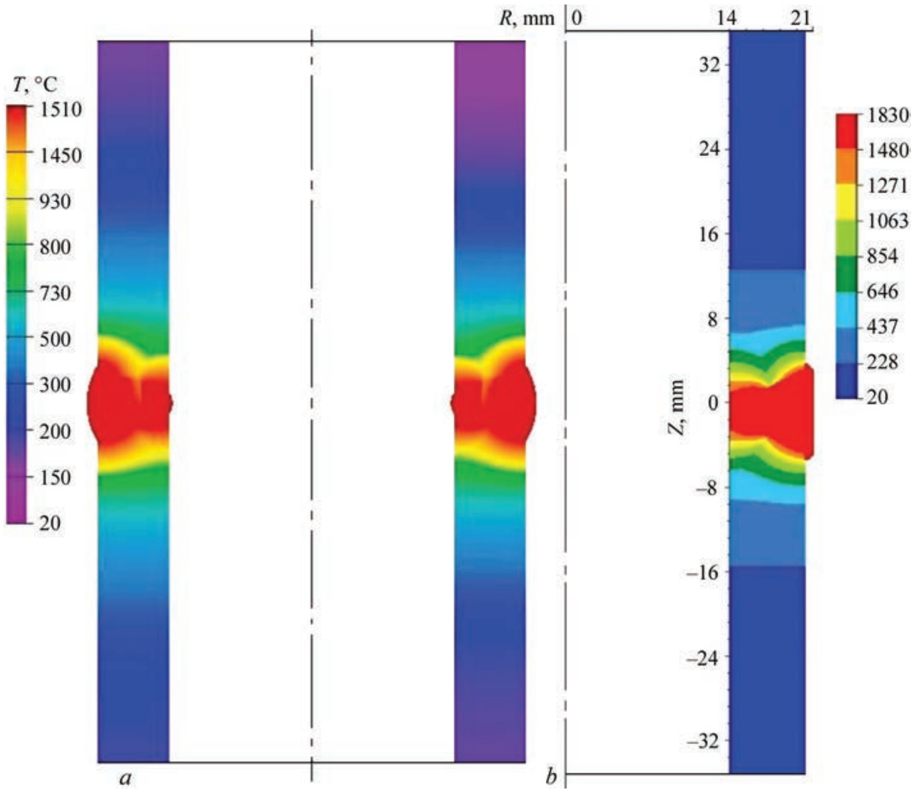

Figure 9. Comparison of calculated distributions of maximum temperature and FZ (red color) in the cross section of a girth welded joint: *a* — 3D model; *b* — 2D model by software "Girth Weld"

Figure 10 shows the calculated distributions of welding residual stresses (circumferential component). In the FZ, where the filler material has an austenitic microstructure, high tensile stresses of up to 450 MPa are produced. In the HAZ of the base material of 12 % Cr steel (lower part of the pipe in Figure 10), due to martensitic transformation, local high compressive stresses of up to –350 MPa appear, as well as local tensile stresses of up to 180–300 MPa according to 2D analysis and up to 50 MPa according to 3D analysis, which balance the compressive stresses. The width of the zone of tensile circumferential residual stresses in the pipe is quite small (approximately 2.0 mm). Further, on the periphery of the pipe

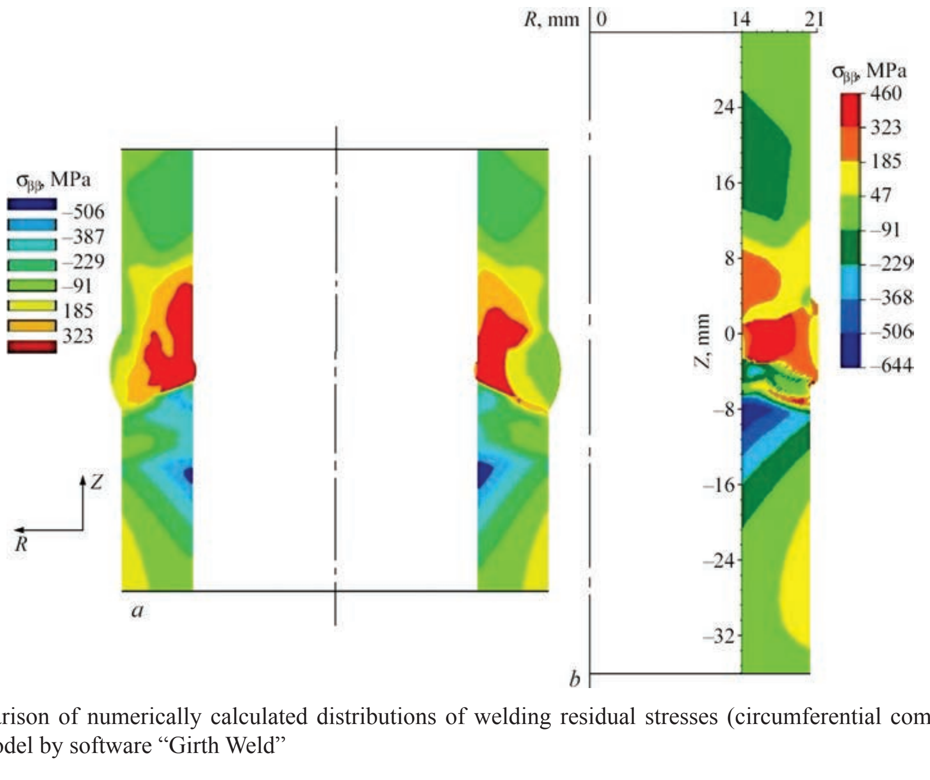

Figure 10. Comparison of numerically calculated distributions of welding residual stresses (circumferential component): *a* — 3D model; *b* — 2D model by software "Girth Weld"

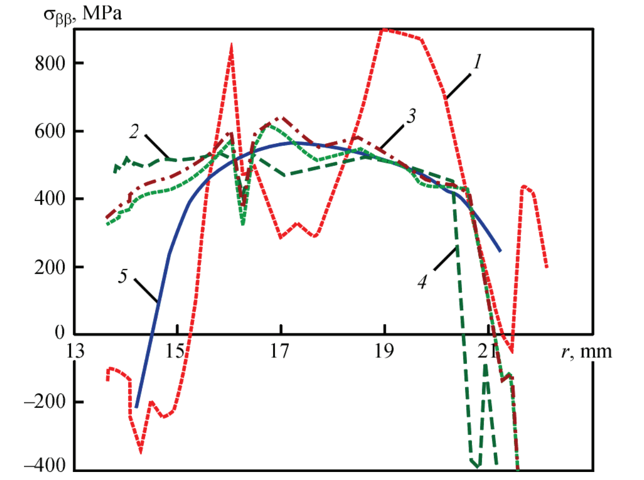

Figure 11. Residual circumferential stresses through the thickness in the center of welded joint for the 2D model and for the 3D model in different sections along the angular coordinate from the start-end of the welding (0, 90, 180, 270°): *1* — start-end; *2* — 90°; *3* — 180°; *4* — 270°; *5* — 2D

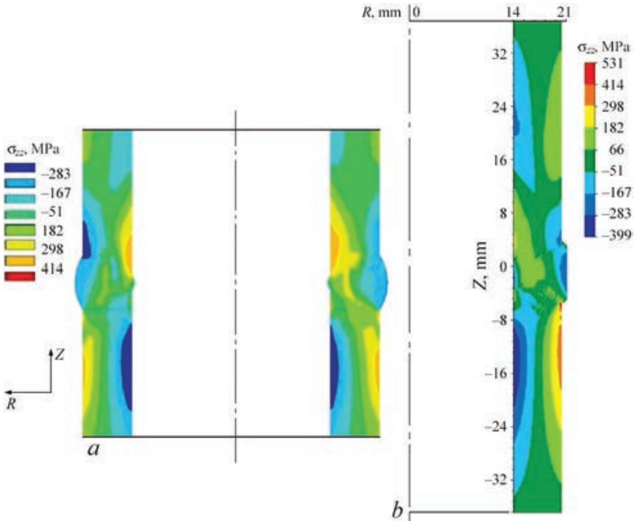

Figure 12. Comparison of numerically calculated distributions of welding residual stresses (axial component): *a* — 3D model; *b* — 2D model "Girth Weld"

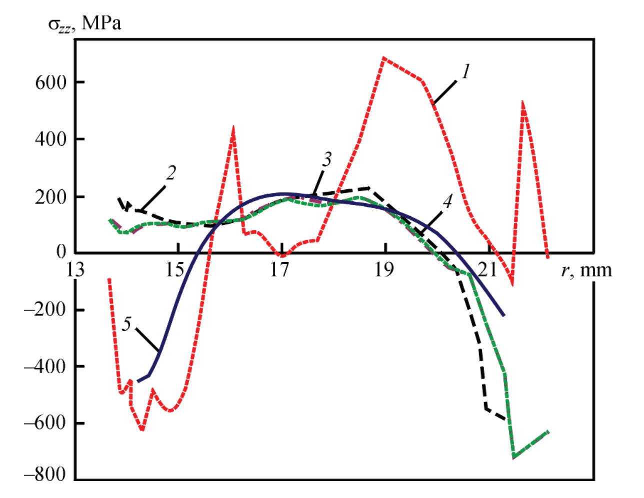

Figure 13. Residual axial stresses through the thickness in the center of welded joint for the 2D model and for the 3D model in different sections along the angular coordinate from the start-end of welding (0, 90, 180, 270°): *1* — start-end; *2* — 90°; *3* — 180°; *4* — 270°; *5* — 2D

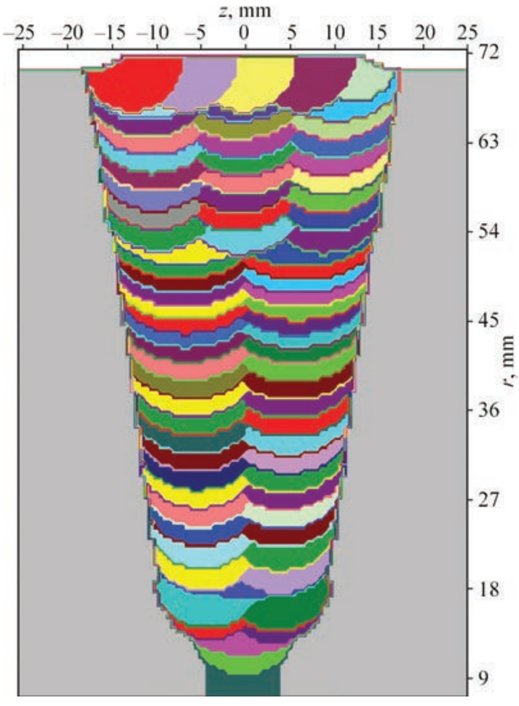

Figure 14. Simulation results of the weld groove filling (weld passes arrangement) for the girth joint of MCP DN-850

made of 12 % Cr steel, compressive stresses of up to –640 MPa are produced on the inner surface and tensile stresses of up to 180 MPa on the outer surface. Figure 11 shows the residual circumferential stresses through the thickness in the center of welded joint for the 2D model and for the 3D model in different sections along the angular coordinate from the start-end of welding (0, 90, 180, 270°). One stress curve differs significantly from the other due to the effect of the start and end of welding in the 3D model. In general, the circumferential stresses determined by the 2D model are close to the results by the 3D model.

The results of the distribution of welding residual stresses for the axial component in Figures 12 and 13 according to the 2D and 3D models also agree well. The martensitic structure of the 12 % Cr steel causes

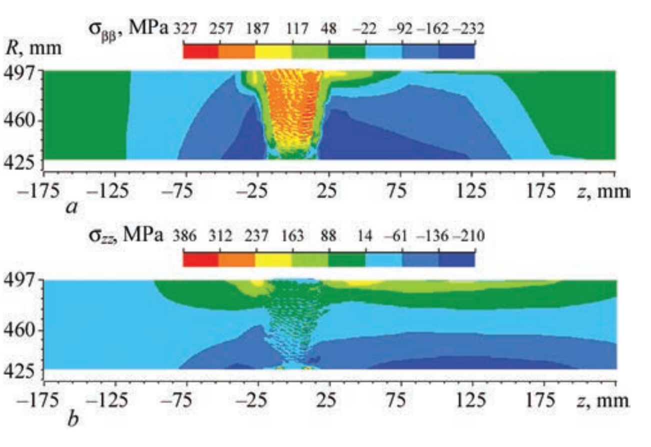

Figure 15. Calculated data on the distribution of residual stresses in the circumferential weld zone of MCP DN-850 after PWHT: *a* — circumferential component; *b* — axial component

a change in the traditionally produced residual axial tensile stresses on the inner surface to compressive stresses up to –400 MPa and, accordingly, of the compressive stresses on the outer surface to tensile stresses up to 400 MPa. This effect can be positive for pipes with a corrosive environment on the inside.

Despite the slight difference in the distribution of residual stresses determined by the 3D model in different cross-sections of the pipe by the angular coordinate, a good agreement with the 2D model is obtained. Thus, the 2D model of the girth weld joint can be used to simulate the distributions of maximum temperatures, microstructural phase composition, mechanical properties, residual stresses and strains in multipass welding of a butt joint of pipelines and cylindrical shells (vessels).

VALIDATION OF MULTIPASS WELDING SIMULATION FOR A PIPELINE GIRTH WELDED JOINT

Calculations performed using the “Girth Weld” computer program provided comprehensive information regarding the distribution of residual welding stresses throughout the volume of the welded joint of the main circulation pipeline (MCP) DN-850 for WWER-1000 type reactors. For validation of the simulation results, experimental measurement data were used. These measurements were carried out on a specimen-model of the girth welded joint of MCP DN-850 on accessible surfaces of the welded components after PWHT, in order to compare with the calculated data.

The computational methodology is based on sequential tracking of the development of temperature fields, stresses, and deformations during the step-by-step filling of the weld groove with weld passes (Figure 14). For each pass, based on experimental data on the parameters of the GTAW process in an argon environment, the dimensions of the FZ and the HAZ of the base material (steel grade 10GN2MFAA) were determined. Based on the size of the FZ and the chemical composition of the filler (Sv-08G1NMA wire), the chemical composition of the metal for each weld pass was calculated.

To simulate the microstructural phase transformations in the FZ and HAZ of low-alloy steels during welding, an approach based on the use of parametric

Table 2. Welding parameters for the girth joint of MCP DN-850 (using ∅ 0.9 mm wire)

Welding passes	Welding parameters					
	I, A pulse/pause	U, V	v, mm/min	Wire feed rate, v_f, mm/min, pulse/pause	Time, μs pulse/pause	Argon flow rate, l/min
First root pass (1)	150/120	9.5	80	880/360	100/100	20–25
Smoothing layer (2)	160/90	10	86	–	100/100	
Third root pass (3)	220/130	11.5	91	2000/1000	225-275	
Fourth root pass (4)	250/150	11.5	89	2600/1300	225/275	
Intermediate filling layer (5–8)	300/180	11.5	89	3400/1620	225/275	
Main filling layer (9–104)	340/200	12	110	3200/1620	225/275	
Reinforcement layer (105–112)	260/110	11.5	80.3	1520/1000	175/325	

Table 3. Mechanical and thermophysical properties of 10GN2MFA steel depending on temperature [1]

T, °C	E·10^{-5}, MPa	$\sigma_T(T)$, MPa	λ, J/(cm·s·°C)	$c\gamma$, J/(cm^3·°C)	v	α, 1/°C
100	2.01	488	0.375	3.88	0.25	1.14
200	1.96	466	0.370	3.98	0.25	1.18
300	1.90	443	0.360	4.21	0.25	1.22
350	1.87	415	0.355	4.44	0.25	1.25
400	1.85	380	0.350	4.76	0.25	1.30
500	1.78	355	0.337	5.10	0.25	1.34
600	1.70	300	0.320	5.80	0.25	1.39
700	1.60	200	0.305	7.35	0.25	1.42
800	1.50	60	0.285	8.10	0.25	1.47
900	1.35	40	0.280	5.60	0.25	1.52
1000	1.15	20	0.275	5.00	0.25	1.65
1100	1.00	20	0.270	4.90	0.25	1.70
1200	1.00	20	0.267	4.90	0.25	1.62

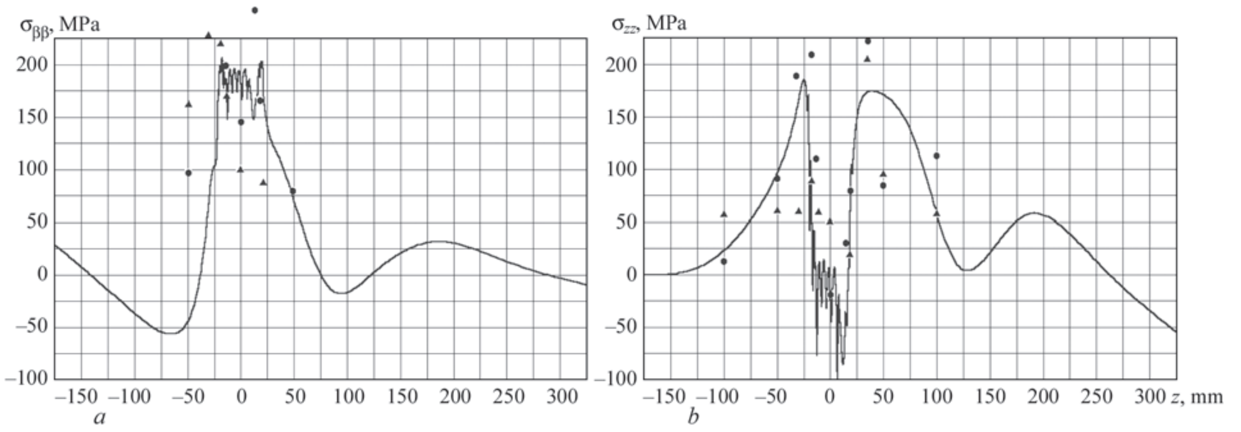

Figure 16. Comparison of calculated and experimental data on residual stress distribution on the outer surface of the MCP DN-850 welded joint [1]: *a* — circumferential component; *b* — axial component

(regression) equations developed at the PWI [8] can be applied.

According to the kinetics of microstructural transformations in the weld metal and the HAZ, the volumetric effects were determined at respective time moments *t* and temperature *T*. For steel grade 10GN2MFAA, dependencies (8) were used to determine the parameter γ_j.

The yield stress of the finite volume material at temperature *T* allowing for the microstructural phase changes was calculated according equation (9). For the type of steels considered, data for the yield stress of the *j*-th microstructure of the material at temperature *T* are presented in Figure 16.

The creep function coefficients for the base material of the welded joint (steel 10GN2MFA) were determined in [1] based on processing of experimental data: $n = 5$, $A = 8.46\cdot10^{17}$ MPa$^{-(n+1)}\cdot h^{-1}$, $G = -66394$ °C.

Experimental measurements were performed on a welded and heat-treated specimen-model of a welded joint with standard processing. Measurements were carried out on the surfaces, i.e., in places accessible for installing strain gauges and further drilling holes to implement the well-known Matara method. Measurements were performed at 24 locations. Figure 16 shows a comparison of calculated and experimental data on the distribution of residual stresses on the outer surfaces of the MCP DN-850, which confirmed the rather high accuracy of the calculation method for determining residual welding stresses.

CONCLUSIONS

The software "Girth Weld" allows in the typical cases of circumferential (girth) welded joints of pipelines and pressure vessels to obtain information on the mechanical properties of the weld metal and HAZ, residual stresses and deformations, to determine the redistribution of the stress-strain state as a result of PWHT, the influence of operational and test loads, to predict the structural integrity and service life of welded structures with discontinuity defects, which are detected as a result of non-destructive testing or postulated.

The computer program is oriented for engineering and scientific application and does not require the user to have special knowleadge in the calculation methods due to the full automation of the processes of creating a mathematical model, dividing the area into finite elements, finding a solution and visualizing the results.

At the same time, the software provides high accuracy of prediction results with limited requirements for computer and time resources due to the use of modern approaches to modeling physical and chemical processes in welding and economical algorithms for solving nonlinear problems and systems of high-order differential equations.

Calculations were carried out for two test problems that are of practical interest and show the main declared capabilities of the computer program "Girth Weld". The verification results indicate that the physical models and processes implemented in the computer program are correct, correspond to the accepted modern approaches for the description of physico-chemical processes during welding heating, mechanics of a deformable body and fracture mechanics. Based on the satisfactory agreement of the calculation results with the experimental measurements on the test sample of the girth welded joint of the pipeline DN850 of the first circuit of the WWVER-1000 reactor made of pearlitic steel, the software "Girth Weld" has been validated and can be used for modeling mechanical properties and the stress-strain state in the zone of butt circumferential welded joints of pipelines and pressure vessels.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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