CALCULATION OF CRITICAL DEPTH OF EDGE CRACK IN THE MAIN OIL PIPELINE IN THE NEIGHBORHOOD OF A TRANSVERSE WELDED JOINT

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Abstract

A numerical method for calculating the critical depth of an edge semi-elliptical crack in the main oil pipeline in the zone of a transverse weld was developed. To calculate the structural composition of steel after welding and the residual welding stresses is used the author-developed finite element software package in Fortran Visual environment. The nonlinear nonstationary heat conductivity problem was solved by the finite difference method using the boundary conditions of third kind. Modeling of the kinetics of conversion of austenite to ferrite and bainite under nonisothermal conditions during welding was carried out based on the theory of isokinetic reactions. The calculation of the residual welding stress is performed by solving the problem of thermoelastic plasticity using the finite element method for material with nonstationary structure. The calculation of the crack resistance is based on Irwin's force failure criterion, and the dependence of the failure viscosity on the structural composition is considered. The ANSYS finite element software was used for calculating the maximum stress intensity factor along the edge of an edge semi-elliptical longitudinal crack in the pipeline. The distribution of fracture toughness as a function of the distance to the weld center is presented, as well as the results of crack resistance analysis in the form of dependences of the critical crack depth on the distance to the middle of the weld and the ratio of the crack half-length to its depth.

Keywords and phrases: Phase and structural transitions, residual welding stresses, finite element method, crack resistance.

AMS subject classification (2010): 74A50, 74A10, 65M60.

1 Introduction

The oil trunk pipelines are connected into a single line using the electric-arc butt welding of separate pipes. Here, the failure of the oil pipelines most often occurs due to destruction in the neighborhood of the transverse welded joint. In this context, the analysis of crack resistance of the pipeline in the zone of the welded butt joint is an extremely relevant problem. The crack resistance of the pipeline in the neighborhood of the welded joint can be estimated based on Irwin's force criterion [1] comparing the maximum calculated value of the stress intensity factor (SIF) along the front of the crack from the action of the residual welding and operating stresses with the failure viscosity (critical value of the SIF), which depends on the structural composition and varies along the pipe section. Thus, the main problem is calculation of the residual welding stresses.

The aim of this paper is to develop a method and software tools to analyze crack resistance of an oil trunk pipeline in the zone of the welded butt joint.

It is known [2] that the most dangerous residual welding stresses in the pipelines are the circumferential stresses. The maximum operating stress in the thin-film pipes from the internal pressure are also circumferential. In this context, the longitudinal cracks, the plane of which coincides with the plane of action of the circumferential stresses, are studied in this paper. First, the total stresses from operation and welding are determined. Further, the SIF along the front of such cracks is calculated in the finite element complex ANSYS. It should be noted that the estimated determination of the residual welding stresses is related to the significant difficulties. This is explained by the fact that the welding process is characterized by a wide temperature range $(20 - 2000^oC)$, where the phase and structural transformations complicating the problem flow in steel. The residual welding stresses can also be defined by the experimental methods [3, 4], but they require the availability of unique expensive equipment and are very labor-intensive. In this respect, the numerical methods of calculation of the residual welding stress in the parts using the standard finite element complexes, for example, ANSYS [5] and ABAQUS [6], come to the foreground. The drawback of the standard finite element complexes is that they do not allow us to consider changes in the phase-structural composition, which significantly influence the thermophysical and physical-mechanical properties of the steel. This leads to a large error when calculating the residual welding stresses. The finite element complex "Welding" should be mentioned separately [7]. In this paper, the kinetics of the structural transformations is described according to a method based on the theory of isokinetic reactions [8] using the information taken from the isothermal transformation diagrams (ITDs) of the undercooled austenite.

In the studies on the analysis of crack resistance of the parts described in the literature, the tabulated formulas only for the cracks in the infinite bodies are used to determine the SIF [9].

It should be noted that, after welding, the structural composition of steel along the pipe section near the welded changes, that is why the failure viscosity K_{Ic} included into Irwin's criterion is also not constant along the pipe section. This fact should be considered in the calculations for the adequate estimation of crack resistance.

2 Calculation Method of the Residual Welding Stresses

In this paper, the calculation of the welding residual stresses during electric-arc butt welding of two pipes 10 mm thick with an internal diameter of 700 mm made of steel 17G1S was determined. The width of the welding bath was assumed equal 20 mm, and the thickness was equal the pipe thickness; the initial temperature of the welding bath was 2000 ℃ (average heating temperature during electric-arc welding). At the initial moment of cooling, the temperature of the pipe beyond the joint zone was assumed equal to 20 ℃.

Modeling of formation of the residual welding stresses has been carried out numerically using the step calculation method, at which three problems are consequently solved at each time step: nonlinear nonstationary heat conductivity, modeling of the phase-structural composition, and calculations of stresses.

For am isotropic body, in the case of variable thermophysical coefficients, the nonlinear asymmetric problem of heat conductivity is described by the differential equation [10]

$$c\rho \frac{\partial T}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial T}{\partial z}\right) + q_V, \tag{1}$$

where $T(r, z, \tau)$ is the temperature, τ is time; c is the heat capacity coefficient, λ is the heat conductivity coefficient, ρ is the density, q_V is the capacity of the specific energy release sources.

To describe the heat transfer conditions, boundary conditions of third kind are used [10]. Because the time of joint welding significantly exceeds the time of cooling of the pipe, at the initial moment of time, the temperature of the whole joint is 2000 ℃, and the temperature of the welded pipe is 20 ℃. Equation (1) was solved by the finite difference method having better convergence as compared to the finite element method. The total approximation method was used during the calculation, at which two one-dimensional equations were solved based on the efficient splitting scheme instead of solving a two-dimensional equation. The algorithm of calculation of the temperature fields in the bodies with the rectangular boundaries by the finite difference method is described in detail in [11].

The liquid-solid transformation in the process of crystallization during welding was simulated using the condition diagram of the iron-carbon alloys. According to this diagram, at temperatures higher than the liquidus temperature T_L, the alloy is in the liquid condition, the first crystals appear during cooling to this temperature, and at the solidus temperature T_S the metal completely transforms to the solid phase—austenite. The specific share of the solid phase was determined based on the condition that $V(T_L) = 0$, and $V(T_S) = 1$ according to the formula of the section rule

$$V = \frac{T_L - T}{T_L - T_S}, \tag{2}$$

According to condition diagram for steel 17G1S with the carbon content $0,17\%$, $T_L = 1530$ ℃, and $T_S = 1490$ ℃ was assumed.

The heat emissions during crystallization of the alloy were considered by including the capacity of the specific energy release sources into the heat conductivity equation. When solving the problem by the step method, this capacity at the n-step was determined for each node of the finite-difference grid

$$q_V^n = \rho \cdot L_{cr} \cdot \frac{\Delta V_n}{\Delta \tau_n},$$

where L_{cr} is the specific heat of alloy crystallization, $\Delta V_n = V_n - V_{n-1}$ is the change of the specific share of the solid phase at the time n-step $\Delta\tau$.

The value of the specific share of the solid phase at n-step and $n-1$-step can be determined according to formula (2) inserting the temperature of n-step and $n-1$-step into it.

The value of the specific heat of crystallization and transformations were assumed as follows [11]: $L_{cr} = 250kJ/kg$, $L_f = 66,7kJ/kg$ and $L_b = 56,3kJ/kg$. The alloy density is $\rho = 7,8 \times 103kg/m3$.

Let us pass to modeling of the structure formation in the process of welding. It is known [12] that when heating over the temperature 740–760 oC, austenization of steel occurs. To describe the isothermal decomposition of austenite into ferrite and bainite, the Kolmogorov–Avrami–Mehl equation was used [9]

$$v(\tau) = 1 - \exp\left(-K_{f(b)}\tau^{n_{f(b)}}\right), \tag{3}$$

where $V_{f(b)}$ is the specific share of ferrite (bainite) and, $K_{f(b)}$, $n_{f(b)}$ are the temperature-dependent empirical coefficients determined according to the isothermal diagram of tube steel 17G1S [13].

For the transfer to the nonisothermal transformation kinetics, the theory of isokinetic reactions [9] was applied, according to which the specific share of ferrite (bainite) at the time n-step is determined according to Eq.(3) for the time, where is the time required to achieve the transformation degree accumulated by the moment at the temperature T_n. In this case, the volume ratio of ferrite (bainite) at n-step can be calculated according to the formula [11]

$$V_{f(b)}(\tau_n) = \Big(1 - \exp\Big\{ - K_{f(b)}(T_n)$$

$$\times \Big[\Big(- \frac{\ln(1 - V_{f(b)}^{n-1})}{K_{f(b)}(T_n)}\Big)^{1/n_{f(b)}(T_n)} + \Delta\tau_n\Big]^{n_{f(b)}(T_n)}\Big\}\Big) V_a^f$$

where V_a^f is the specific share of the austenite after passing the ferrite range. For the ferrite range, $V_a^f = 1$.

During numerical modeling, the vector of the specific shares of austenite, ferrite, and bainite was calculated at each time step, in each finite element, respectively $\{V\} = \{V_a,]; V_f,\ V_b\}$, which was used to calculate the thermophysical and physical-mechanical characteristics at the next step.

The calculation of the stresses was carried out by the finite element method solving the problem of thermo-elasto-plasticity for material with a nonstationary structure [11]. The solution was based on the step method of the additional (initial) deformations. In this case, the increment of the total deformation tensor for each finite element is given by

$$\Delta\varepsilon_{ij} = \Delta\varepsilon_{ij}^e + \Delta\varepsilon_{ij}^0,$$

where $\Delta\varepsilon_{ij}^0 = \Delta\varepsilon_{ij}^p + \delta_{ij}\Delta\varepsilon_T$ is additional deformation; $\Delta\varepsilon_{ij}^e$ and $\Delta\varepsilon_{ij}^p$ are the increments of the elastic and plastic deformation; δ_{ij} is the Kronecker delta; $\Delta\varepsilon_T = \alpha\Delta T$ is the increment of the free deformation; α is the coefficient of thermal expansion depending on the temperature and composition; and is the temperature change at this step.

According to the method of additional deformation, the solution of the thermo-elasto-plasticity problem is reduced to the sequential solution of the thermoelasticity problem by the finite element method.

When determining the increments of the plastic deformations, the existence of the plastic potential was assumed, which for the nonisothermal flow theory in the case of a nonstationary structural composition and use of the Huber-Mises plasticity criterion can be given by [11]

$$F_p = (3/2 S_{ij} S_{ij})^{1/2} - f_T(q_p, Q) = 0,$$

where S_{ij} is the stress deviator; $q_p = \int d\bar{\varepsilon}_i^p$ is the Odqvist parameter upon plasticity and $d\bar{\varepsilon}_i^p$ is the intensity of the increments of the plastic deformations; Q is parameter characterizing the temperature and the structural condition of steel.

The function f_T can be received from the instantaneous extension curves. When using the model of the elastoplastic medium with power hardening for the extension curves of some certain structures, the instantaneous extension curve of the heterogeneous structure can be given by

$$\sigma = E\varepsilon \quad \text{at} \quad \varepsilon \le \varepsilon_y = (\sigma_{ya}V_a + \sigma_{yf}V_f + \sigma_{yb}V_b)/E,$$

$$\sigma = \sigma_{ya}\left(\frac{\varepsilon}{\varepsilon_{ya}}\right)^{m_a} V_a + \sigma_{yf}\left(\frac{\varepsilon}{\varepsilon_{yf}}\right)^{m_f} V_f + \sigma_{yb}\left(\frac{\varepsilon}{\varepsilon_{yb}}\right)^{m_b} V_b \quad at \quad \varepsilon > \varepsilon_y,$$

$$\varepsilon_{ya} = \sigma_{ya}/E, \;\; \varepsilon_{yf} = \sigma_{yf}/E, \;\; \varepsilon_{yb} = \sigma_{yb}/E,$$

where σ is the stress; E is the elasticity modulus; ε is the deformation; $\sigma_{ya}, \sigma_{yf}, \sigma_{yb}$ and m_a, m_f, m_b are the yield strengths and hardening indices depending on the temperature for austenite, ferrite-carbide, and bainite, respectively.

All thermophysical coefficients and physical-mechanical characteristics were assumed according to [11].

3 Modeling Results and Analysis

In Fig. 1, the distribution of the residual welding circumferential stress in the longitudinal section of the pipe is presented. Due to the symmetry of the problem for the plane passing through the middle of the welded joint, only the right upper part of the pipe 80 mm long is shown. Here, for convenience of perception of the picture, the scale by the pipe thickness was selected as three times more than by the length.

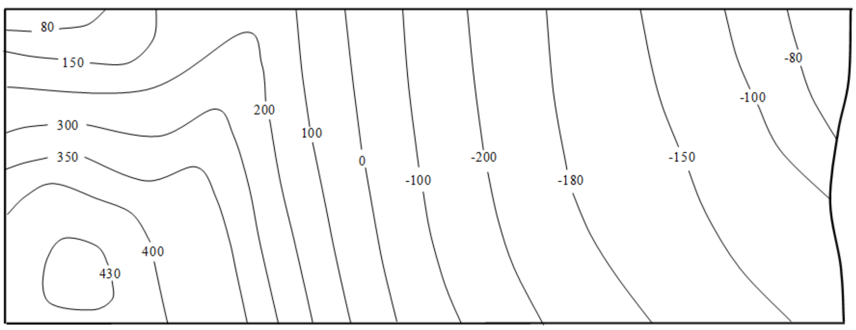

Figure 1:

It is seen from Fig. 1 that the circumferential stresses in the range of the welded joint are tensile along the total thickness of the pipe and become compressive at a distance of about three thickness from the middle of the welded joint. The range of the maximum tensile stresses achieving 430 MPa is within the welded joint near the internal surface of the pipe. Thus, the most dangerous range for the appearance of the longitudinal edge cracks is the range of the welded joint and near-joint range on the internal surface of the pipe.

The failure viscosity K_{Ic} depends on the structural composition, which varies along the pipe section in the neighborhood of the transverse welded joint. In the first approximation, the failure viscosity of the heterogeneous structure can be determined according to the rule of mixture proportionally to the specific shares of ferrite and bainite

$$K_{Ic} = K_{Ic}^{f} V_f + K_{Ic}^{b}(1 - V_b), \tag{4}$$

where $K_{Ic}, K_{Ic}^{f}, K_{Ic}^{b}$ are the failure viscosity of the heterogeneous structure, ferrite and bainite, respectively. The failure viscosity values of ferrite and bainite were assumed equal to $K_{Ic}^{f} = 60\text{MPa}\sqrt{m}$ and $K_{Ic}^{b} = 40\text{MPa}\sqrt{m}$ according to [14].

The calculations of the structural compositions have shown that the pipe structure changes only at a distance of about 15 mm from the middle of the welded joint. Further, the structure does not change and represents ferrite. In the middle of the welded joint, the heterogeneous structure represents 14 % of the ferrite and 86 % of the bainite. In Fig. 2, the dependence K_{Ic} of the failure viscosity on the distance S from the middle of the welded joint is presented calculated according to formula (4) for the internal (curve 1) and middle (curve 2) surface of the pipe.

The calculation of the SIF by the front edge of the longitudinal semielliptical cracks located on the internal surface of the pipe was conducted in the finite element complex ANSYS using the superposition principle. According to it, the total circumferential stresses have been applied to the crack edges, which are present in the pipe without a crack in the place of the longitudinal section where the crack is really available.

The total stresses were determined by adding the welding stresses to the operating stresses. For the internal pressure in the pipe equal to 7.5 MPa, the operating circumferential stresses were 266 MPa. When applying the total stresses to the crack edges, the nonuniform distribution of the stresses by the crack edges were considered. The whole pipe was not considered, only a sector 200 mm long. The choice of such a length was specified by the fact that, as the calculations show, the residual welding stresses completely decay at such a distance from the welded joint. It has been stated during the numerical experiment that it is sufficient to consider the pipe sector with a central angle of 10^o.

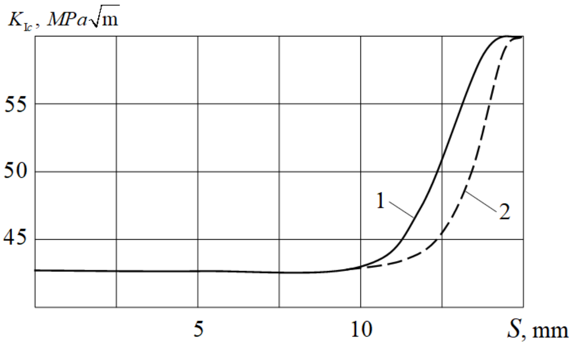

Figure 2:

To construct the mathematical model, 10-node tetrahedral finite elements SOLID 187 were used, and to describe the features along the crack front, the special singular 15-node prismatic finite elements SOLID 186. The total number of elements was 16 603. In Fig. 3, the results of calculation of the SIF along the front of such a crack are given. It is clear that the SIF at the deepest point of the crack front is equal to $35,4\text{MPa}\sqrt{\text{m}}$, and in the point coming to the surface, it is $21,9\text{MPa}\sqrt{\text{m}}$.

The calculation of the crack resistance was carried out based on Irwin's force criterion

$$K_I^{\max} \leq K_{Ic}$$

where $K_I^{\max}$ is the maximum value of the SIF along the crack front.

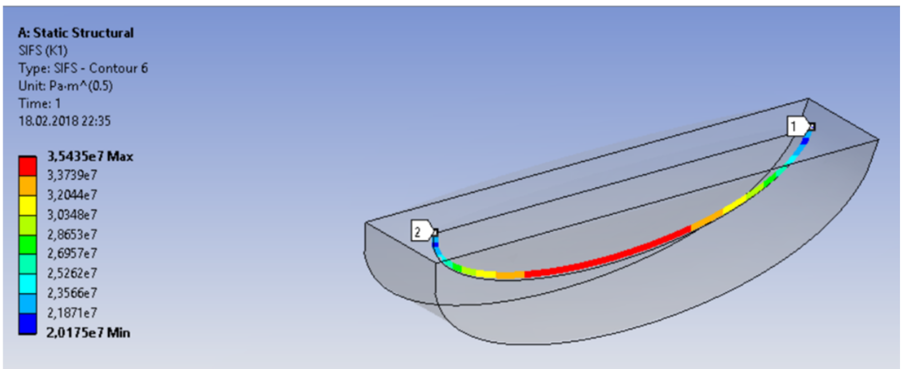

Figure 3:

The value $K_I^{\max}$ was determined by means of the SIF analysis at three points of the crack front: at the deepest point and at two points coming to the surface. It was considered that the failure condition was fulfilled if the SIF at one of these three points achieved the critical value. The dependence of the critical crack depth on the distance from the center of the welded joint S and the relation of half of the length of the crack to the depth for the most dangerous zone of the pipeline is given in Fig. 4. It is seen that an increase in the crack length leads to a decrease in the critical crack depth: *1*, 1; *2*, 3; *3*, 5.

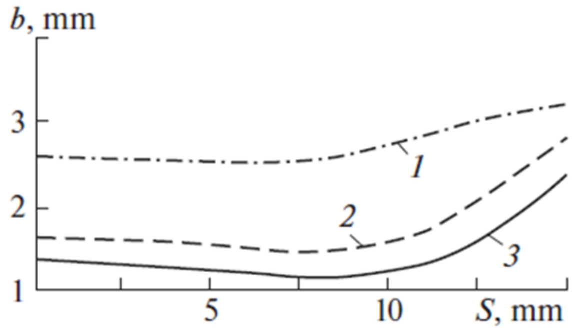

Figure 4:

With an increase in the relation of half of the length to the depth, this influence decelerates. With relations 1 and 3, the critical depth differs by almost two times, and the difference in the depth with relations 3 and 5 makes up about 30 %. The most dangerous case is when the center of the crack is located at a distance of approximately 7.5 mm to the middle of the welded joint. It is seen from Fig. 1 that the maximum residual welding circumferential stresses are observed precisely in this zone.

4 Conclusions

The failure viscosity (critical value of the SIF) changes only at a distance of about 15 mm from the middle of the welded joint and further assumes a constant value. The most dangerous are the longitudinal crack-like defects located on the internal side of the welded joint. Here, extensive cracks are more dangerous. The least dangerous are cracks located remotely from the welded joint at a distance exceeding twenty times the pipe thickness, where the residual welding stresses decay and the failure viscosity is maximum. Analysis of the crack resistance of welded pipelines not considering the residual welding stresses is not possible as these stresses exceed the operating stresses in the zone of the transverse welded joint.

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