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SIMULATION OF A MANUAL ELECTRIC-ARC WELDING IN A WORKING GAS PIPELINE. 2. NUMERICAL INVESTIGATION OF THE TEMPERATURE-STRESS DISTRIBUTION IN THE WALL OF A GAS PIPE

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A numerical simulation of the action of the current experienced by an electric arc and the rate of gas flow in a pipe of a cross-country gas pipeline on the depth of penetration of the electric arc into the wall of this pipe and on the current and residual stresses arising in the pipe material in the process of electric-arc welding of nonthrough cavity-like defects in it has been carried out for gas pipes with walls of different thickness.

Keywords: *mathematical simulation, numerical investigation, electric-arc welding, temperature stresses, cross-country gas pipeline, penetration depth.*

Introduction. The main problem arising in the process of repair work in a gas pipe of a working gas pipeline is the provision of a required quality of the welded joint without disturbance of the integrity and normal operation of the gas pipeline. The obtaining of a high-quality welded joint under the conditions where it is intensively cooled from within the pipe by the gas flowing in it is a very complex problem. To solve this problem, it is necessary to determine the maximum temperature of the welded joint, the rates of its cooling and heating, the endurance of this joint to the action of critical temperatures, the influence of the velocity of movement of the electrode on the welding parameters, and so on. Calculation of the welding parameters is a fairly cumbersome procedure, and it is often impossible to determine these parameters experimentally. Therefore, simulation and prognostication methods hold much promise for solving this problem [1, 2]. Moreover, the development of a technology of repair works carried out with the use of a manual electric-arc welding on the basis of a computational experiment makes it possible to decrease the time of these works as well as the expenditures of time, labor, and material resources.

We describe a computational experiment on determination of the influence of the strength of the current in an electric-arc heat source on the depth of penetration of the arc into the wall of a gas pipe subjected to electric-arc welding and on the level of the current and residual stresses in the gas-pipe walls of different thickness as well as the influence of the rate of the gas flow in a gas pipe on the distributions of temperatures and stresses in its material.

Numerical Investigations of the Influence of the Current Experienced by an Electric Arc on the Depth of Penetration of the Arc into the Material of a Gas Pipe and on the Current and Residual Stresses in It on the Basis of the Model Proposed in [1]. A simulation was carried out for the standard conditions of electric-arc welding: H = 7.5, 10, and 12 mm (Fig. 1), v_{el} = 1.3 mm/s, U = 22 V, I = 80, 90, 100, 110, and 120 A, and T_0 = 290 K.

Mathematical description of the heat transfer in a plate is based on the heat-conduction equation [3]. The mechanism of formation of deformations and stresses in a gas pipe in the process of welding was considered in detail in [1, 2, 4–13]. The power of an electric-arc heat source (a heat flow) was determined by the formula

$$q_{el} = \frac{AIU}{S_{el}} \exp\left(-k\left[(x - v_{el}t)^2 + y^2\right]\right). \quad (1)$$

The coefficient of utilization of the arc power A in this equation accounts for both the heat lost in the environment and the energy expended for the melting of the electrode and the welding wire; traditionally, A = 0.5–0.7 (in this case,

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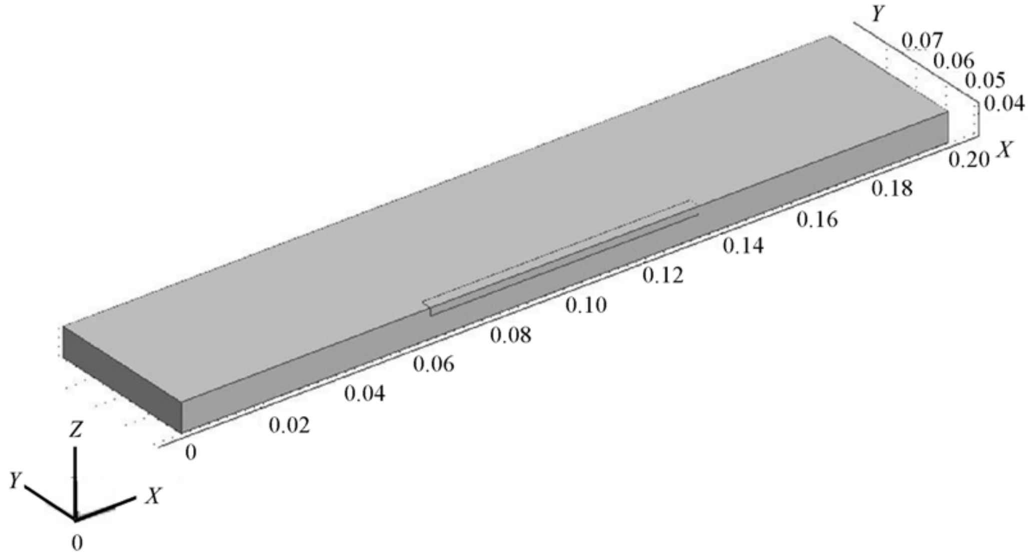

Fig. 1. Region of a pipe of a cross-country gas pipeline.

TABLE 1. Influence of the Thickness of the Walls of a Gas Pipe and the Time of Action of an Electric-Arc Source on It on the Penetration Depth of the Pipe Material

H, mm	I, A	t, s	h, mm
7.5	80	15	1.9
		30	4.1
	100	15	5.1
		30	5.5*
	120	15	5.5
		30	5.5
10	120	15	3.4
		30	6.2
12	120	15	2.6
		30	3.1

*The temperature at the inner surface of the gas pipe is higher than the melting temperature of its material.

$A = 0.5$) [3]. The concentration coefficient k was taken to be equal to $2.0 \cdot 10^4$. The Gaussian form of the coordinate dependence points to the fact that the arc has a hot core and a relatively cold periphery; the difference $x - v_{el}t$ accounts for the movement of the heat source along the X axis with velocity v_{el}. The region S_{el} is bounded by the quantities $q_{el}(r) \geq 0.005 q_{max}(r)$, and $r^2 = (x - v_{el}t)^2 + y^2$.

The heat transfer from a surface region of a gas pipe to the environment is estimated by the law of convective heat exchange with the environment

$$q = \alpha (T - T_{env}) . \qquad (2)$$

The heat exchange of the pipe surfaces $z = H$ and $z = 0$ with the air was estimated with the use of the coefficient of convective heat transfer α equal to 15 W/(m^2·K). The heat flow from the other surfaces bounding the pipe region being considered was taken to be equal to zero, i.e., it was assumed that, at these boundaries, a heat exchange with the environment is absent.

The thermophysical (heat capacity, heat conductivity, density) and mechanical (Young modulus, yield stress, hardening coefficient) parameters of the material of a gas pipe subjected to electric-arc welding, with which the computational experiment was carried out, were determined as functions of the temperature [1, 2, 4, 5, 14] of the pipe material.

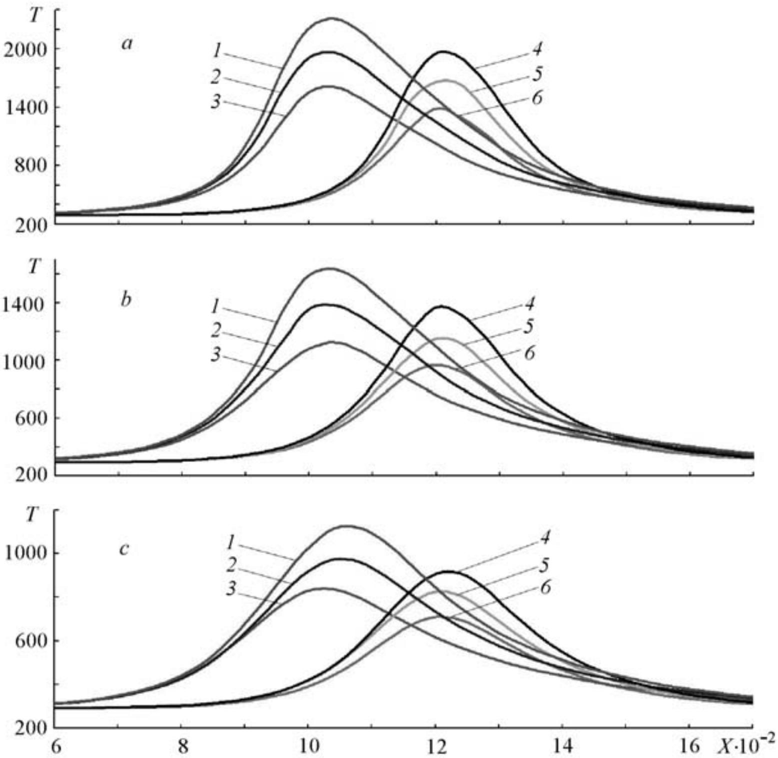

Fig. 2. Temperature distribution at the inner surface of a gas pipe of thickness 7.5 mm (a), 10 mm (b), and 12 mm (c) at α = 15 W/(m^2·K): 1) I = 120, t = 30; 2) 100, 30; 3) 80, 30; 4) 120, 15; 5) 100 A, 15 s; 6) 80 A, 15 s.

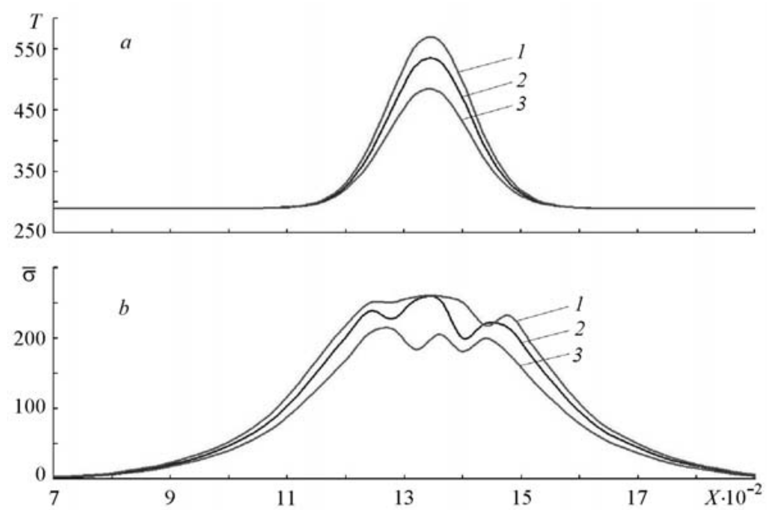

Fig. 3. Distributions of temperatures (a) and stresses (b) at the inner surface of a gas pipe of thickness 7.5 mm at 1.12 s at α = 15 W/(m^2·K) and I = 120 (1), 100 (2), and 80 A (3).

As a result of the computational experiment on simulation of the process of electric-arc welding of nonthrough defects like cavities in a gas pipe of a cross-country gas pipeline in the absence of a gas flow in it, we obtained the penetration depths and the distributions of temperature fields, deformations, and stresses in this pipe at different instants of time (see Table 1) and constructed the corresponding graphic dependences of the indicated quantities (Figs. 2–5). When the depth (region) of penetration of the arc into the material of the gas pipe was determined,

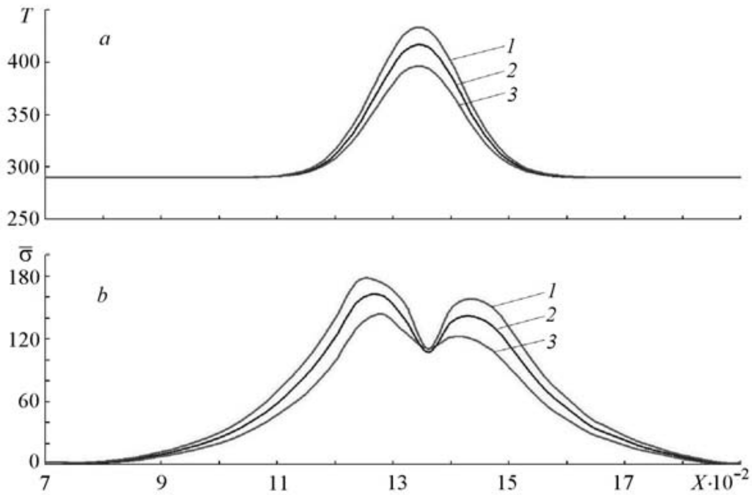

Fig. 4. Distributions of temperatures (a) and stresses (b) at the inner surface of a gas pipe of thickness 10 mm. Designations 1–3 are identical to those in Fig. 3.

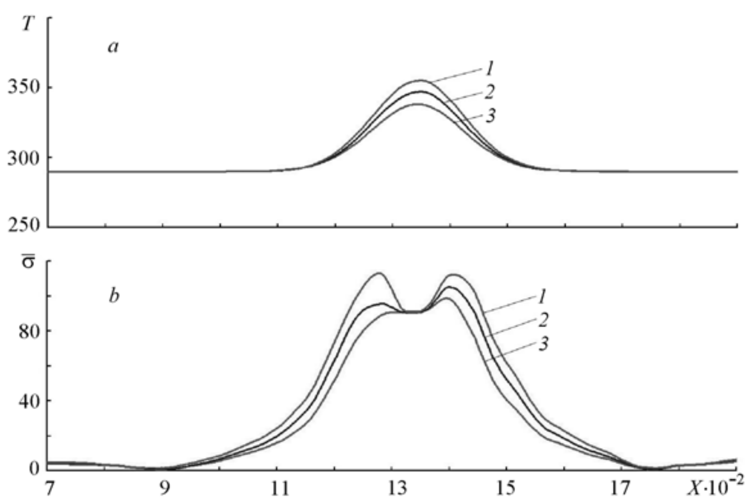

Fig. 5. Distributions of temperatures (a) and stresses (b) at the inner surface of a gas pipe of thickness 12 mm. Designations 1–3 are identical to those in Fig. 3.

the calculated values of the temperature field were compared with the melting temperature of the pipe material. The melting temperature was determined by the diagram of state of carbon steels; for steels with a carbon content of 1.7% (17GS mark) it is equal to 1640 K. The depth of the welded defect was taken to be equal to 2 mm for the pipes with walls of thickness 7.5 and 12 mm and equal to 2.5 mm for the pipe with a wall of thickness 10 mm. The penetration depth h was measured from the bottom of the defect in the direction to the inner surface of the pipe. At the instant of time 480 s, the stresses comprised 0.1–0.4 MPa.

To determine the dependence of the penetration depth of the wall of a gas pipe and the maximum temperatures and stresses arising in the pipe material in the process of its welding on the current strength, corresponding nomograms were constructed [2].

Our calculations have shown that the larger the wall of a gas pipe, the smaller the penetration region: as the thickness of the pipe wall increases, the rate of cooling of the penetration region increases due to the predominant transfer of heat into the depth of the wall of the pipe. The depth of the penetration region of the steel increases with increase in the strength of the current experienced by the electric arc. However, the current and residual stresses change insignificantly in this case and their level does not exceed the ultimate strength of the steel at a corresponding temperature.

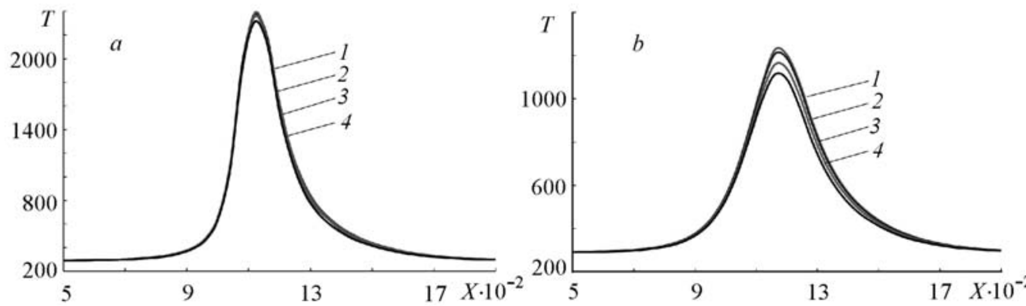

Fig. 6. Temperature distributions at the outer (a) and inner (b) surfaces of a gas pipe for the heat-transfer coefficient α = 15 (1), 58 (2), 139.8 (3), and 273.2 W/(m^2·K) (4).

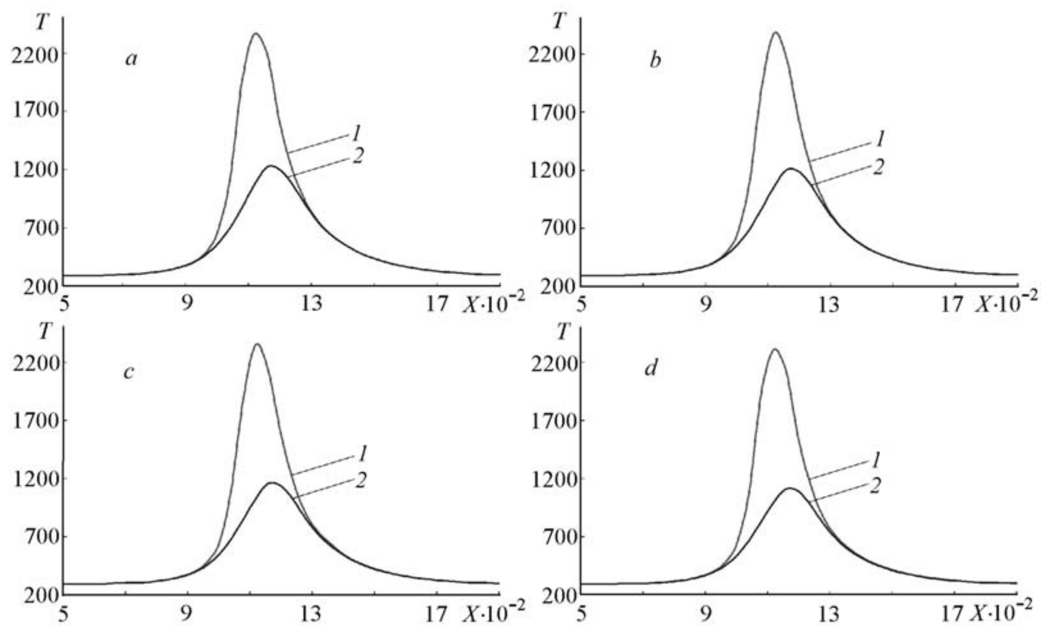

Fig. 7. Temperature distributions at the outer (1) and inner (2) surfaces of the pipe region subjected to the welding for the heat-transfer coefficient α = 15 (a), 58 (b), 139.8 (c), and 273.2 W/(m^2·K) (d).

The dependence of the maximum surface temperature of a gas pipe on the thickness of its wall and the strength of the current carried by the electric arc is identical to the dependence of the penetration depth on the indicated quantities, i.e., as expected, the temperatures at the outer and inner surfaces of the wall of a gas pipe decrease with increase in the thickness of the pipe wall and increase with increase in the current strength. For example, when the thickness of the pipe wall increases from 7.5 to 12 mm (by 60%) at a current strength of 80 A, the maximum temperature at its inner surface decreases from 1611 to 802 K (by ~50%). When the current strength increases from 80 to 120 A (by 50%), the maximum temperature at the inner surface of the pipe with a wall of thickness 7.5-mm increases from 1611 to 2313 K (by ~44%), which substantially exceeds the melting temperature of the pipe material.

It should be noted that when the strength of the current experienced by the electric arc increases from 80 to 120 A, the temperature stresses at the outer surface of a gas pipe with a wall of thickness 10 mm increase from 292 to 313 MPa (by ~7%) and the temperature stresses at its inner surface increase from 144 to 179 MPa (by ~24%); these stresses are much lower than the allowable ones (~300 MPa for the 17GIS steel). An analysis of the dependence of the residual stresses in the wall of the indicated gas pipe on the increase in the current strength has shown that these stresses at the inner surface of the pipe increase by 63% and the stresses at its outer surface increase by 82% in this case. However, the level of the indicated stresses is not high: they range from approximately 0.09 to 0.34 MPa.

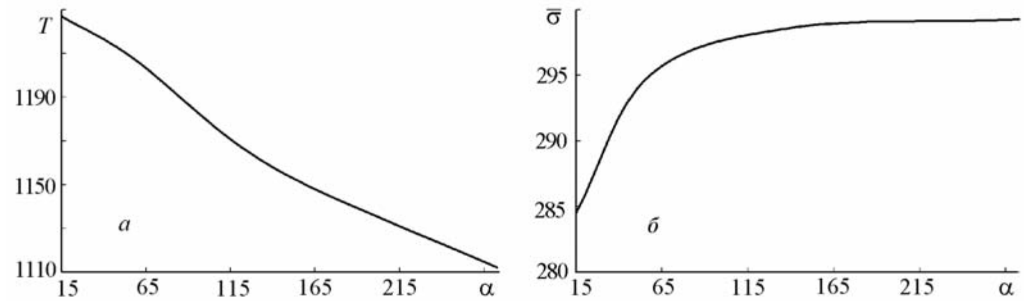

Fig. 8. Dependence of the maximum temperature (a) and maximum stress (b) on the heat-transfer coefficient at the inner surface of a gas pipe.

Therefore, the probability of destruction of such a pipe seems to be insignificant because of the low level of stresses arising in it.

Numerical Investigation of the Influence of the Velocity of the Gas Flow in a Pipe on the Distribution of Temperatures and Stresses in It. In the process of welding-up of defects in a gas pipe, the temperature field penetrates into the body of the pipe; in this case, the working conditions should be such that the temperatures at the inner surface of the pipe be safe for the welding works in the presence of a gas flow inside the pipe. These conditions can be determined on the basis of the analysis of the influence of the velocity of the gas flow inside the pipe on the temperature field at its inner surface. A computational experiment was carried out for electric-arc welding of a nonthrough defect of depth 2 mm in the wall of a gas pipe of thickness 7.5 mm in the case where the current experienced by the arc was equal to 100 A. A varying parameter was the coefficient of convective heat exchange between the gas in the pipe and its inner wall; it was assumed to be equal to 58, 139.8, and 273.2 $W/(m^2{\cdot}K)$.

As a result of the computational experiment, we obtained the temperature distributions in the wall of a gas pipe for different heat-transfer coefficients. The temperature distributors along the length of the pipe region being investigated at the 20th second from the beginning of the process are presented in Figs. 6–8.

The calculation data obtained point to the fact that the rate of gas flow in a gas pipe and, consequently, the heat-transfer coefficient do not exert a significant influence on the temperature distribution in the pipe wall. Since the stresses in the wall of a gas pipe are mainly determined by the temperature fields in it, the velocity of the gas flow in the pipe will insignificantly influence the temperature distribution in its wall. A more descriptive dependence of the maximum temperature and the stresses in a gas pipe on the heat-transfer coefficient is presented in Fig. 8. It is seen that the increase in this coefficient from 58 to 273.2 $W/(m^2{\cdot}K)$ (by ~371%) causes the maximum temperature in the wall of the pipe to decrease insignificantly — by only 115 K (~9%); in this case, the maximum stresses increase by 14 MPa (~5%).

The results obtained have a clear physical sense. Since the velocity of movement of the "maximum" of the heat-source power and the velocity of the heat outflow on the surface of a gas pipe are equal, for every point of the pipe surface subjected to electric-arc welding the statement that the lower the power of the electric-arc heat source, the lower the temperature at the inner surface of the pipe and, consequently, the lower the power of the heat outflow due to the convection is true. For example, in the case where an electric-arc heat source possessing a power two orders of magnitude larger than the power of the convective heat outflow acts on the surface of a gas pipe, the distributions of temperatures and stresses in the pipe material depend weakly on the coefficient of heat exchange between the wall of the pipe and the gas in it. Therefore, the parameters of the process of welding of nonthrough defects in a gas pipe should be determined for the "worst" case of absence of convective heat transfer from the inner surface of the pipe. At the end of the welding process, where the electric-arc heat source is turned off, the convective heat transfer will influence the rate of cooling of the pipe, which was observed in [1, 2]. Moreover, in the case where the powers of the heat source and the heat outflow are commensurable, the heat-transfer coefficient influences the temperature and stresses at the wall of the pipe. It should be noted that the results of the computational experiment depend critically on the velocity of movement of the electrode, and it is impossible to determine this velocity exactly for a manual electric-arc welding. In this connection, a technique of repair works in a working gas pipeline should be developed for the worst conditions of the welding process, namely, for the conditions where a convective heat transfer from the inner surface of a gas pipe is absent and the velocity of movement of the electrode is as small as possible (we recommend using the infrared-spectroscopy method for determining the velocity of movement of the electrode) [15].

Conclusions. The renovation of a cross-country gas pipeline and provision of its safe operation is impossible without repair work, the safety of which should be estimated. In the majority of cases, a welding is used for liquidation of defects in the wall of a gas pipeline. In the process of welding, high-temperature fields arise in this wall, which increases the risk of an accident with an ignition of the pumped gas. If the technological parameters of the repair are selected correctly, the risk of an accident can be reduced to zero and all planned works can be done successfully. The cost of the indicated investigations can be decreased with the use of a computer simulation of the welding process. As compared to ordinary nature experiments, the computer simulation calls for large preliminary works on the development of models in the form of computer programs. However, the further experiments with the use of these models are much more operative, inexpensive, and efficient.

In particular, on the basis of the model developed, we carried out a numerical experiment on estimation of the depth of penetration of an electric arc into nonthrough defects with a depth comprising approximately 25% of the thickness of the wall of a gas pipe and on determination of the maximum temperatures, deformations, and stresses at the inner and outer surfaces of the pipe at a definite current experienced by the electric arc for pipe walls of different thickness.

The experimental results have shown that the current and residual stresses arising in pipes with walls of thickness 10 and 12 mm in the process of their electric-arc welding do not exceed the ultimate strength of these pipes, which allows the conclusion that the welding regimes selected (80 A $\le I \le$ 120 A) do not give rise to additional defects in the stressed-strained material of the pipe.

Our investigations of the influence of the gas-flow rate in a gas pipe on the distributions of temperatures and stresses in the pipe wall in the process of welding of nonthrough defects in it allow the conclusion that in the case where an electric-arc heat source, the power of which is as a rule two orders of magnitude larger than the power of a convective-heat outflow, acts on the surface of a gas pipe, the distributions of temperatures and stresses in the pipe wall depend insignificantly on the velocity of the gas flow in the gas pipeline (for the working pressure 2 MPa $\le \Delta P \le$ 4 MPa). At the end of the welding process, where the electric-arc heat source is turned off, the convective heat exchange will influence the rate of cooling of the pipe, which was observed in [1, 2]. An extremely important parameter is the velocity of movement of the electrode, determined directly, in the case of a manual welding, by the qualification of a welder.

Thus, a computational experiment can be used as an efficient means for determining the optimum and safe conditions of repair work in gas pipelines, carried out with the use of electric-arc welding, in particular, for determining the allowable strength of the current carried by the electric arc, at which the through penetration of the pipe walls of definite thickness is excluded.

NOTATION

A, coefficient of utilization of the arc power; h, penetration depth, m; H, thickness of the wall of a gas pipe, m; I, strength of the current carried by the arc, A; k, concentration coefficient; q, heat flow from the surface of the pipe, W/m^2; q_{max}, power of the electric-arc heat source at the center of the computational region, W/m^2; q_{el}, power of the electric-arc heat source per unit area, W/m^2; r, distance from the center of the electric-arc heat source, m; S_{el}, area of the spot of the electric-arc heat source, m^2; t, time of action of the electric-arc source on the surface of the gas pipe, s; T, surface temperature of the gas pipe, K; T_0, initial temperature of the pipe region, K; T_{env}, environmental temperature, K; U, electric voltage (potential difference) across the electrode and the pipe, V; v_{el}, velocity of movement of the electric-arc heat source (electrode), m/s; x, distance along the X axis, m; y, distance along the Y axis, m; z, distance along the Z axis, m; α, coefficient of convective heat transfer, W/(m^2·K); $\overline{\sigma}$, value of the voltage, Pa. Subscripts: env, environment; el, electric-arc; max, maximum; 0, initial.

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