Management of thermal process for polyethylene gas pipes welding with built-in heater

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Abstract. Based on the thermal process control, rapid welding technology for polyethylene pipes with built-in heater in the open air at temperatures below standard is proposed. Technological parameters of welding are determined by calculation from the condition of temperature field dynamics in heat-affected zone according to regularities, that are peculiar to welding at permissible temperatures. The results of determining the welding parameters during electrofusion welding and welding of the saddle branch to the polyethylene pipe of the gas pipeline, as well as the results of tests of the joints obtained by the proposed welding technology are presented.

1. Introduction

According to regulatory documents, welding of polyethylene gas pipes using fittings (couplings, saddles, tees, etc.) is recommended to be performed at ambient air temperature from minus 15 °C to plus 45 °C. With a wider temperature range, welding is recommended to be performed in rooms (shelters) that ensure compliance with the specified temperature range. Welding in shelters is associated with high energy costs and long preparatory work, which is unacceptable in emergency situations. Even a rather short interruption of gas supply in winter conditions in regions of cold climate can lead to disastrous consequences due to an accident of heating systems. A pressing problem is the development of technology for the rapid welding of polyethylene pipes at low temperatures without using shelters.

In this paper, we consider thermal processes of coupling welding of polyethylene pipes and welding of saddle branches to polyethylene pipes at air temperatures below standard. In the considered methods of welding of polymeric pipes, reflooding is performed by a heating element in the form of a metal spiral integrated into the connecting piece. At ambient air temperatures below the normative, it is proposed to control heat welding process by preheating and using thermal insulation at the cooling stage. Preheating is performed by heating element when voltage is applied that prevents the material from melting. Temperature equalization to temperature acceptable for welding is performed with the power supply turned off. Melting is performed by welding machine automatically in normal mode, simulating the average design temperature in the heat-affected zone on the ambient air temperature sensor. Preheating, temperature equalization, reflow and cooling of the welded joint are performed under a layer of thermal insulation, thickness of which for a certain air temperature is preliminarily calculated from the condition of the joint cooling according to the pattern characteristic of welding under the conditions of acceptable air temperature.

Control of thermal process of welding at low temperatures is reduced to provision of technological parameters (voltage for heating, duration of heating, duration of temperature equalization, thickness of
the insulation layer) determined by calculation. Determination of welding parameters will be illustrated with examples.

2. Formulation of the problem

It is obvious that effectiveness of heat welding process controlling depends on adequacy of mathematical model to the real process. In polymeric materials, phase transformations occur in temperature ranges [1]. The temperature distribution during welding of polyethylene pipes is described by equation of thermal conductivity considering two-phase zone during melting and crystallization of polymer material [2-4]:

\[
\left( c(T) + \rho \cdot L^{\text{100}} \frac{dX_c}{dT} \right) \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda(T) \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda(T) \frac{\partial T}{\partial z} \right) +
\]

\[
+ \frac{Q(T)}{n \cdot 2\pi r} \delta(r-R_i) \sum_{i=1}^{n} \delta(z-z_i), \quad r, z \in \Omega, \quad 0 < t \leq t_n,
\]

where \( Q \) is power of the heat source; \( L^{\text{100}} \) is specific heat of phase transformation of completely crystalline polymer; \( X_c \) – degree of crystallinity;

\[
c(T) = \rho^c \cdot c^+ + X_c(T) \cdot (\rho^c \cdot c^- - \rho^c \cdot c^+), \quad \lambda(T) = \lambda^c + X_c(T) \cdot (\lambda^- - \lambda^c),
\]

\( c^-, \rho^-, \lambda^- \) and \( c^+, \rho^+, \lambda^+ \) – specific heat capacity, density and thermal conductivity for solid and liquid phases of pipe material, respectively; \( n \) – amount of concentrated heat sources; \( r, z_i \) – heat source location; \( \delta \) - Dirac delta function.

Degree of crystallinity \( X_c \) is determined by formula:

\[
X_c(T) = \begin{cases} 
X_c^\infty, & T \leq T_1, \\
\int_0^T q(u) du, & T_1 < T < T_2, \\
0, & T \geq T_2.
\end{cases}
\]

Here \( q(u) \) – dependence of heat flux on temperature, referred to unit mass of a substance, recorded by a differential scanning calorimeter (DSC); \( X_c^\infty \) – maximum degree of crystallinity of the studied polymeric material; \( v_T \) - temperature change rate.

After differentiating integral in function (2) over variable upper limit, we have:

\[
\chi(T) = L^{\text{100}} \frac{dX_c}{dT} = \begin{cases} 
0, & T \leq T_1, \\
-\frac{q(T)}{v_T}, & T_1 < T < T_2, \\
0, & T \geq T_2.
\end{cases}
\]

We obtain following equation for temperature in entire computational domain \( \Omega \):

\[
\left( c(T) - \rho^c \chi(T) \right) \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda(T) \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda(T) \frac{\partial T}{\partial z} \right) +
\]

\[
+ \frac{Q(T)}{n \cdot 2\pi r} \delta(r-R_i) \sum_{i=1}^{n} \delta(z-z_i), \quad (r, z) \in \Omega, \quad 0 < t \leq t_n,
\]
Equation (4) is supplemented by initial
\[ T(x,0) = T_0, \quad (r, z) \in \Omega, \] (5)
and boundary conditions, where \( T_0 \) is ambient temperature. Power of heat source is calculated by formula:
\[ Q(t) = \frac{U^2}{R \cdot (1 + \beta(T - 20))}, \] (6)
where \( R \) is resistance of electric heating coil at temperature 20 \(^\circ\)C; \( \beta \) – temperature coefficient of resistance.

Convective heat exchange \( \alpha \) at the contact of the pipe and the coupling (saddle branch) with thermal insulation is determined from the expression [5]:
\[ \frac{1}{\alpha} = \frac{1}{\alpha_o} + \frac{h_c}{\lambda_c}, \] (7)
where \( h_c \) is the thickness of the thermal insulation layer, \( \lambda_c \) is the thermal conductivity of the insulation material, \( \alpha_o \) is the heat exchange with the environment.

The computational domain \( \Omega \) triangulation was performed using Gmsh mesh generator. The task (4- (8) was solved by finite element method using the free-access program Dolfin/FEniCS. The visualization of the results obtained was implemented using Paraview package.

3. Calculation of electrofusion welding parameters
In axisymmetric formulation, problem of determining a non-stationary temperature field during coupling welding of polyethylene pipes PE100 SDR 11 63\( \times \)5.8 at an ambient air temperature of -47 \(^\circ\)C was considered. Figure 1 displays the design scheme of a half of pipe with a coupling. Figure 2 shows temperature distribution after preheating by heating element for 540 seconds until the temperature near the spiral reaches 50 \(^\circ\)C and equalizing the temperatures for 2 minutes at ambient temperature minus 47 \(^\circ\)C. The voltage for preheating was 9 V, thickness of thermal insulation layer was 2 cm. Calculations show that the average temperature is about 15 \(^\circ\)C in the field of welding. Heating (reflow) can be made according to the regulated mode.

![Figure 1. Design scheme: 1 – pipe; 2 – coupling](image1)

![Figure 2. Temperature distribution in cross section of coupling and pipe with heat insulation at ambient air temperature of minus 47 \(^\circ\)C after preheating for 540 s and equalizing for 120 s](image2)

Figure 3 shows a comparison of the dimensions of the fused zone in the vertical section when welding at different ambient temperatures at the cooling time for 1 minute after completion of heating. According to calculations the size of the fused zone decreases at low temperatures below minus 15 \(^\circ\)C that indicate a smaller volume of the resulting melt. Consequently it will result in insufficient pressure of welded surfaces, more intensive crystallization and formation of a fine structure of the weld material, etc., which lead to a low strength of the joint. Figure 2 (b) shows the cooling time for 1
minute at ambient temperature of minus 47 °C with preheating and thermal insulation and temperature of 5 °C (standard welding). The temperature distributions in the heat-affected zone in both cases are close after the same cooling times that demonstrates formation of identical structures causing the same strength of the joints.

Figure 3. Heat-affected zones in cross section of coupling and pipe during cooling for 1 minute after heating at the ambient temperatures 5 °C (a) and minus 47 °C (b) with preheating and equalizing under thermal insulation.

Figure 4 shows the results of tests on the exfoliation of welded joints obtained at low temperatures. According to the maximum breaking load, the quality of the joints is higher than the quality of the joint obtained at the permissible temperature. The highest values are obtained for the compound obtained for preheating to 50 °C.

Figure 4. The values of the maximum breaking load of coupling welded joints, obtained at different ambient temperatures. (In brackets the maximum temperatures reached during heating.)

4. Calculation of welding saddle parameters.
Welding of saddle 110/63 to polyethylene pipe PE 100 SDR 11 110 × 10.0 was considered at an ambient temperature of -45 °C. (Fig. 4, A). Consider the design model (Fig. 5 (a)): 1 – saddle branch 1, 2 – polyethylene pipe, 3 – heating element. Figure 5 (b) shows the temperature distribution after preheating for 13.5 minutes and equalizing for 4 minutes. The voltage for preheating was 17 V and the thickness of the thermal insulation layer was 2 cm. The results of preheating and temperature equalizing calculations show that in the area of welding the average temperature is about 15 °C.
Figure 5. General view of the saddle branch and pipe (a) and temperature distribution in the joint after preheating for 810 seconds with voltage of 17 V and equalizing for 120 seconds (b).

Calculations of the temperature distribution after heating at different cooling moments were also considered. Figure 6 shows results during cooling for 8 minutes at temperatures of -45 °C with preheating and thermal insulation and 0 °C (standard welding). The temperature distributions in the heat-affected zone at low and permissible temperatures are close after the same cooling time that indicates the identity of the crystallization process, which leads to an equivalent strength of the joint. The crystallization process is completed on the ten minute of cooling in both cases.

Figure 6. Heat-affected zones in cross section of saddle branch and pipe during cooling for 8 minute after heating at the ambient temperatures 0 °C (a) and minus 45 °C (b) with preheating and equalizing under thermal insulation.

Breaking loads of tested saddle branches are almost the same (Fig. 7), which testifies to the effectiveness of the proposed technology for welding of saddle branch to polyethylene pipe at ambient temperatures below standard.
Figure 7. Breaking load of saddle branch welded at ambient air temperatures of 18 °C (standard welding) and minus 45 °C (according to the proposed technology)

5. Conclusion.
Testing the quality of welded joints has determined the effectiveness of proposed method for calculating the technological parameters of polyethylene pipes welding with built-in heaters at ambient temperatures below the normative ones based on mathematical modeling of the thermal process, considering phase transformation in the temperature range.

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