Analysis of Temperature Field Dynamics in Electrofusion Welding of Polymer Pipes at Low Temperatures

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Abstract. Technique for determining technological parameters of electrofusion welding of polyethylene pipes at ambient temperatures below standard, based on analysis of temperature field dynamics in heat-affected zone, is proposed. Mathematical model of thermal welding process used in calculations is presented, considering temperature dependence of phase transformation heat and crystallinity degree of polymer material. Results of determining parameters for electrofusion welding of polyethylene pipes and welding of branch saddle topload to polyethylene pipe are presented. Effectiveness of calculated determination of welding parameters is confirmed by tests of welded joints made according to proposed welding technology at naturally low temperatures.

1. Introduction

The development of technology for welding polymer pipes at low temperatures is closely related to the mathematical modeling of the heat process, which determines the formation of the welded joint material. The control of the thermal welding process at low air temperatures to achieve the thermal regime, at which high-quality connection is obtained, is carried out based on numerical analysis of the temperature regime. At the same time, successful management largely depends on how adequately and fully the mathematical model considers the main phenomena that affect the thermal welding process. After melting, the greater or lesser part of the polymeric substance passes into crystalline state at the cooling stage, depending on the temperature regime. The polymer contains two phases in the solid state: crystalline and amorphous. Even though the crystalline part is stronger than amorphous, high crystallinity degree of the polymer does not guarantee high material strength. Dimensions of supramolecular structures, depending on the cooling rate, are of importance to obtain durable welded joint. It is believed that at an ambient temperature from the interval from minus 15 to plus 45℃, which is recommended by regulatory documents for welding polyethylene pipes, the cooling mode provides the necessary strength of the welded joint. The ambient temperature from the specified interval is called acceptable welding temperature.

Temporary temperature changes at points of the heat-affected zone (HAZ) during welding at conditions of permissible temperatures can be represented as a set of temperature dependences in some “corridors”. In this paper, we propose methods for determining parameters of sleeve welding of polyethylene pipes and welding of saddle branch to polyethylene pipe at ambient temperatures below the acceptable ones, from the condition of providing temporary temperature changes in the heat-affected zone according to dependences of corresponding "corridors" at allowable ambient temperature. In this
case, mathematical model of the thermal process is used, considering the temperature dependence of the heat of phase transformation and the crystallinity degree of the polymer material.

2. Problem statement
Calculations with modeling the temperature field in welded plates and the heating wire, the distance between the turns of which does not exceed $1\text{-}2$ mm, show that at the end of heating the temperature field in the region of the location of turns of the heater becomes almost uniform [1]. This position allows us to present the coupling heater in the form of a ring and saddle branch heater in the form of a curved ring with volumes equivalent to the volume of the spiral of heaters, in order to simplify the geometry of the computational domain. Calculation models (Figure 1) of polyethylene pipe section (region $\Omega_1$) with sleeve or saddle branch (region $\Omega_2$) are considered. Heating and fusion of welding surfaces is carried out by built-in heating element (region $\Omega_3$) when it is connected to a current source.

![Figure 1. Calculation model of pipe section with coupling (a) and saddle branch (b).](image)

During melting and crystallization of polyethylene, the phase transition occurs in the temperature range. It is necessary to consider the intermediate phase between solid $T_1$ and liquid $T_2$ substance, in which the substance is both in solid and in liquid state, to formulate mathematical model [2]. Boundaries of the intermediate phase (two-phase region) are determined by temperatures of solidus and liquidus. The unsteady temperature field during welding of polyethylene pipes in the entire computational domain $\Omega = \bigcup_{i=1}^{3} \Omega_i$ is described by the heat equation:

$$
\left[ c(T) - \rho^\prime \chi(T) \right] \frac{\partial T}{\partial t} = \text{div}(\lambda(T) \text{grad} T) + Q(T), \\
(r, z) \in \Omega, \ 0 < t \leq t_m,
$$

(1)

where

$$
c(T) = \rho^+ c^+ + X_c(T) \cdot \left( \rho^+ c^- - \rho^+ c^+ \right), \\
\lambda(T) = \lambda^+ + X_c(T) \cdot \left( \lambda^- - \lambda^+ \right),
$$

$$
\chi(T) = \int_{T_1}^{T_2} \frac{dX_c}{dT} = \left\{ \begin{array}{ll} 0, & T \leq T_1, \\
-\frac{q(T)}{v_r}, & T_1 < T < T_2, \\
0, & T \geq T_2,
\end{array} \right.
$$

$T$ – temperature; $t$ – time; $t_m$ – estimated time; $c^-, \rho^-, \lambda^-$ and $c^+, \rho^+, \lambda^+$ – specific heat, density and thermal conductivity for solid and liquid phase of pipe material respectively; $Q(t)$ – heat source power;
$L^{100\%}$ – specific heat of phase transformation of fully crystalline polymer; $X_C$ – crystallinity degree; $T_1, T_2$, – solidus and liquidus temperatures; $q(T)$ – temperature dependence of heat flux per unit mass of substance recorded by differential scanning calorimeter (DSC); $\nu_T$ – temperature change rate.

Equation (1) is supplemented by initial and boundary conditions:

$$T(x,0) = T_0, \quad (r, z) \in \Omega,$$

$$-\lambda \frac{\partial T}{\partial n} = a(T)_{\Gamma} - T_0,$$

$$T|_{\Gamma} = T_0,$$

where $T_0$ – ambient air temperature, $\Gamma$ – free lateral and inner surface of the pipe, $\Gamma_T$ – surface of pipe ends.

The general statement of the heat problem for electrofusion welding of polyethylene pipes allows us to consider phase transition heat using DSC data and crystallinity function.

3. Finite elements discretization

For the numerical solution of the problem, we carry out the approximation by the finite element method of equation (1) considering boundary conditions (2) - (4) [3-4]. We multiply the heat equation by the function $v$ and integrate over the domain $\Omega$:

$$\int_{\Omega} (c(T) - \rho \chi(T)) \frac{\partial T}{\partial t} v dx = \int_{\Omega} (\lambda(T) \nabla T \nabla v) dx, \quad x \in \Omega, \; 0 < t \leq t_m.$$

We reduce the resulting equation to variational formulation for each time layer: $a(T^{n+1}, v) = L(v)$.

We define uniform grid in time $\omega_n = \{ t^n = n \cdot \tau, \; n = 0, 1, ..., M, \; \tau = t_m \}$ and approximate in time using the implicit difference scheme and partial integration formula, we obtain:

$$a(T^{n+1}, v) = \frac{1}{\tau} \int_{\Omega} (c(T^n) - \rho \chi(T^n)) T^{n+1} v dx + \int_{\Gamma} (\lambda(T^n) \nabla T^{n+1} \nabla v) dx + \int_{\Gamma} a T^n v ds,$$

$$L(v) = \frac{1}{\tau} \int_{\Omega} (c(T^n) - \rho \chi(T^n)) T^n v dx + \int_{\Gamma} a T^n v ds + \int_{\Omega} Q v dx.$$

The numerical implementation of the computational algorithm is performed based on the FEniCS computational package [4]. Temperature field determination is reduced to solving the system of linear algebraic equations with the help of package library, using the variational statement of the problem and the approximation of the temperature function derivative with respect to time. The construction of the computational domain $\Omega$ and its triangulation were performed using the Gmsh program [5].

4. Calculation of electrofusion welding parameters

Polyethylene pipes of PE 100 SDR 11 110×10,0 brand, coupling and 110/63 saddle branch were used to calculate the unsteady temperature field during socket welding and welding of the saddle branch. The heat source power is calculated by the formula:

$$Q(t) = \frac{U^2}{R \cdot (1 + \beta(T - 20))}$$

where $U$ – voltage, $R$ – resistance of electric heating coil, $\beta$– temperature coefficient of resistance. The material of the built-in heating element for considered welding examples is nichrome.
Convective heat transfer $\alpha$ at the contact of the pipe and coupling (saddle branch) with thermal insulation is determined from the expression [6]:

$$\frac{1}{\alpha} = \frac{1}{\alpha_0} + \frac{h_{iz}}{\lambda_{iz}}$$

where $h_{iz}$ – insulation layer thickness, $\lambda_{iz}$ – thermal conductivity of the insulation material, $\alpha_0$ – heat exchange with the environment. Polyethylene foam with aluminum foil was chosen as heat-insulating material.

Optimal parameters for the duration of preheating and equalization at ambient temperature of minus 45°C were found by controlling parameters of source power for preheating and thickness of the insulation during cooling.

Calculation results for electrofusion welding are considered in further paragraphs. Figure 2 shows temperature distribution after preheating the heating element for 11 minutes and equalizing temperatures for 2 minutes. The voltage for heating was 13 V, the insulation layer thickness was 2 cm.

![Figure 2. Temperature distribution in the section of coupling and pipe after preheating and equalization at ambient temperature of -45 °C.](image)

Figure 3 shows comparison of temperatures in the heat affected zone at the moment of cooling for 10 minutes at ambient temperatures of +5 °C and -45 °C after preheating and leveling is shown. Temperature distributions in the heat affected zone during welding in both cases are close after the same cooling times, which indicates the formation of the same structures, which determine the equivalent strength of joints.

![Figure 3. Heat-affected zone distribution in the section of coupling and pipe at the time of cooling 10 minutes after completion of heating at the temperature: +5 °C and -45 °C with preheating and cooling with thermal insulation.](image)

Now results of calculating the saddle branch welding are considered. Calculations found following technological parameters for saddle branch welding at -45°C: voltage for heating - 17 V, duration of heating 13.5 minutes, duration of temperature equalization 4 minutes, insulation layer thickness 2 cm. Figure 4 shows the temperature distribution in the saddle and the pipe section with thermal insulation at ambient temperature of -45°C after heating and temperature equalization. Heating (reflow) can be done according to regulated regime.
Figure 4. Temperature distribution in the pipe and saddle branch after preheating and equalization.

Calculations of the temperature distribution after welding showed that the HAZ reaches its maximum volume after completion of heating at the second minute of cooling. The cooling of compound under thermal insulation layer with calculated thickness at low temperature proceeds according to consistent pattern, which is distinctive at allowable temperature in the open air. Figure 5 shows comparison of temperatures in the heat affected zone at the cooling for 10 minutes at ambient temperatures of +10°C and -45°C after preheating and leveling is shown. Temperature distributions in the heat affected zone during welding in both cases are close after the same cooling times, which indicates the formation of the same structures, that cause equal strength of the joints.

Figure 5. Heat-affected zonedistribution in the plane section of saddle branch and polyethylene pipe at cooling stage in 10 minutes after heating completion at the temperature: a - +10°C; b - -45°C with preheating and cooling with thermal insulation.

Figure 6 (a) presents peeling test results for obtained welded coupling joints at low temperatures. At the maximum breaking load, the quality of compounds is higher than the quality of the compound obtained at acceptable temperature. The highest rates are set for the compound obtained by heating to 50°C. Breaking loads of tested branch saddles are almost the same (Figure 6 (b)), which indicates the
effectiveness of the proposed technology for welding branch saddles to polyethylene pipes at ambient temperatures below standard.

Figure 6. Values of maximum breaking load of sleeve welded joints (a) and breaking load of saddle branches (b) obtained at different air temperatures.

5. Conclusion
The possibility of obtaining high-quality welded joint at low air temperatures by controlling the thermal process, based on comparative analysis of temperature fields in welded joints made at conditions of permissible ambient temperature and at temperature lower than permissible, is shown. Control parameters of electrofusion welding of polyethylene pipes at temperatures below standard (supplied voltage during heating, duration of preheating and temperature equalization, as well as the thickness of the insulation layer at the stage of cooling of the welded joint) can be determined by calculation using the proposed mathematical model of the thermal welding process.

6. References
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