The Provision of Conditions for the Formation of a High-Quality Weld During Butt Welding of Polyethylene Pipes at Low Ambient Temperature

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Abstract. Welding of polyethylene (PE) pipes for gas pipelines is recommended to be performed at ambient air (AA) temperature from minus 15 to plus 45 °C. The present work proposes a mathematical model of the thermal process for butt-welding of PE pipes, which takes into account the latent heat of phase transitions in the temperature range. Correspondence of the model to the real thermal process is confirmed by comparing the experimental and calculated temperatures. At a temperature from the permissible temperature range in the heat affected zone (HAZ), a cooling rate is provided in the optimum interval, which ensures the formation of the structure of the welded material that provide sufficient strength. Thus, for welding PE pipes at AA temperatures below the normative it is sufficient to establish the cooling rate in the optimum interval in the HAZ while maintaining the other technological parameters of welding. Mathematical modelling shows that the necessary cooling rate in the HAZ is obtained by preheating the ends of the welded pipes to the permissible temperature along the outreach length equal to the fivefold thickness of the pipe, melting in regular mode and cooling the welded joint in the heat-insulating structure of the calculated size.

1. Introduction

Polyethylene pipes have extensive applications in distribution systems of gas supply and in other facilities [1-3]. This is due to the main advantages of these pipes such as strength, flexibility and chemical inertness in comparison with metallic materials, for example, steel [4–5]. There are various ways of connecting polyethylene pipes: butt-, socket-welding, electrofusion, welding with vibration and friction [6–8]. As the length of gas pipelines from polyethylene pipes increases, it becomes extremely important to solve the problem of their immediate repair in emergency situations, especially in the winter period in the northern regions of Russia. Current regulatory documents allow welding during installation and repair works at an ambient air temperature of not below than minus 15 ° C [9]. Let the temperature range from -15 to +40°C be acceptable range. At lower air temperatures, welding is recommended to perform in lightweight heated structures maintaining the temperature from the acceptable range. Meanwhile, such welding involves high energy costs, non-production costs and long preparation, which is unacceptable in emergency situations.

Investigation of the thermal process of butt-welding polyethylene pipes for gas pipelines at air temperatures below the standard is given in [10]. Computational experiments show the possibility of regulating the temperature regime for welding in conditions of low ambient air temperatures and providing the same variation of temperature field in the heat affected zone as at acceptable air temperatures. This is possible at preheating of the pipe ends to be welded, temperature leveling, which precede the heating (fusion) stage at acceptable air temperatures, and cooling the welded joint in the heat-insulating construction. The preheating, equalization and construction dimensions are determined by calculation.

2. Statement of problem and methods of solution

Determination of boundaries of the heat affected zone (HAZ), in which structural changes of the welded materials occur, is of great importance when choosing the technological modes for welding polyethylene pipes, as well as when investigating the quality of the welded joint. Typically, the HAZ is defined experimentally by examining structural indicators. Taking into account the frequently used assumption that structural changes occur at temperatures above the softening temperature of the material [11], the boundaries of the heat-affected zones for different welding regimes are determined theoretically. Failure to observe welding technology and lack of sufficient maintenance leads to defects in the welded joint zone [12-14].

The thermal process during welding is described by the two-dimensional equation of thermal conductivity in cylindrical coordinates:

$$\left(c(T)+\rho_{df}(T)L\frac{d\Theta}{dT}\right)\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda(T)\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right),\ r,z\in\Omega,\ 0<t\le t_m, \quad (1)$$

where L is the specific heat of the phase transition; ρ_f is the density of the phase undergoing the transformation; $\rho_f=\rho^{+}-$ during reflow, $\rho_f=\rho^{-}-$ during crystallization; $\Theta(T)=0,\ T<T_{\Phi};\ \Theta(T)=1,\ T\ge T_{\Phi}$.

Since the phase transition occurs in the temperature range in polymer materials, in mathematical model it is necessary to take into account the intermediate phase between a solid and a liquid substance, in which the substance is in both the solid and liquid states [15]. The heat of the phase transition in the temperature range is considered in various methods, the simplest of which is the formal description of the share of the solid phase in the form of a linear function [16]. Calculation of the formation and growth of crystallization nuclei in the heat of the phase transition by the kinetic equation of isothermal crystallization by Avrami is described, for example, in [17-19]. We use a simpler method of determining the phase transition in the temperature range without the separation of nucleation and their growth, using the total rate of crystallization. We take $\tilde{\Theta}(T)$ function characterizing the share of the liquid phase as an approximation to the Heaviside function Θ(T):

$$\tilde{\Theta}(T)=\begin{cases}0, & T\le T_S,\\ \dfrac{\int_{T_S}^{T}q(u)\,du}{\int_{T_S}^{T_L}q(u)\,du}, & T_S<T<T_L,\\ 1, & T\ge T_L,\end{cases}\qquad L=\frac{(t_2-t_1)\int_{T_S}^{T_L}q(u)\,du}{T_L-T_S} \quad (2)$$

where $q(T)$ is the temperature dependence of the heat flux per unit mass of matter recorded by DSC; T_S, T_L stand for the solidus and liquidus temperatures; L is the specific heat of the phase transition, and t_1, t_2 are the time at which the phase transition begins and ends. Consequently,

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$$\chi(T) = L\frac{d\tilde{\Theta}}{dT} = \begin{cases} 0, & T \le T_S, \\ \dfrac{q(T)}{v_T}, & T_S < T < T_L, \\ 0, & T \ge T_L, \end{cases} \quad (3)$$

where v_T is the heating (cooling) rate, which is varied in the differential scanning calorimeter (DSC). The continuous functions of the heat flux obtained by DSC at a rate of temperature change of 10 K / min and approximated by cubic B splines are used in the calculations [20]. Figure 1 shows the functions of the heat flux used in the calculations for the reflow and crystallization of polyethylene.

Thus, the following equation for the temperature in the entire calculated area is obtained Ω:

$$\left(c(T) + \rho_{df}\chi(T)\right)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda(T)\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right) + \gamma Q(t),\ \ r,\ z \in \Omega,\ 0 < t \le t_m, \quad (4)$$

the coefficients of the equation are expressed by the following relations:

$$c(T) = \rho^- c^- + \tilde{\Theta}(T)\cdot\left(\rho^+ c^+ - \rho^- c^-\right),\ \ \lambda(T) = \lambda^- + \tilde{\Theta}(T)\cdot\left(\lambda^+ - \lambda^-\right),$$

where c^-, ρ^-, λ^- and c^+, ρ^+, λ^+ are the specific heat, density and thermal conductivity for the solid and liquid phases of the pipe material, respectively.

The temperature of the heated tool T_H is set at the pipe end. Taking into account the low thermal conductivity of polyethylene, we assume that the temperature of the pipe does not change at some distance $z = l$ from the weld zone during the entire process. Convective heat exchange takes place with the surrounding air on the outer and inner surfaces of the pipe (figure 2).

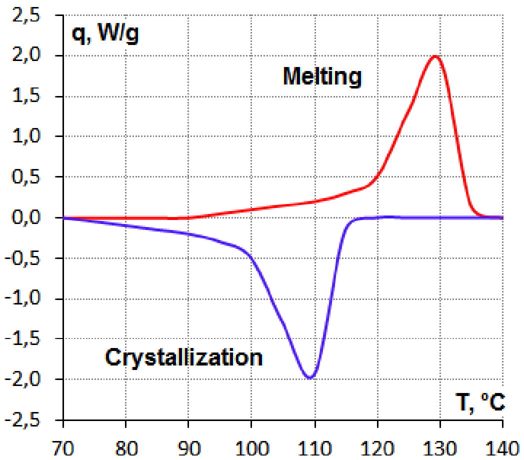

Figure 1. Dependences of the heat flux during crystallization and melting of polyethylene on temperature, recorded by DSC

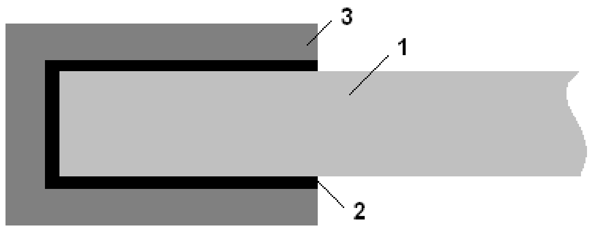

Figure 2. Scheme of the pipe wall 1 with heater 3 and elastic element 2

Fusion, technological pause and junction of welded surfaces were performed according to the regimes regulated by reference documents. Modelling of the thermal process of butt-welding with preheating were accomplished for SDR 11 63×5.8 polyethylene pipe at various ambient temperatures. The calculations were performed with the following data: inner radius r_1 = 0.0257; outer radius r_2 = 0.0315 m; λ^- = 0.38; λ^+ = 0.29 W / (kg · °C); ρ^- = 954; ρ^+ = 700 kg / m^3; c^- = 2100; c^+ = 1900 J / (kg · °C) [21]. The length of the heated area of the heating tool was 3 cm. The ambient temperature was 20, minus 15 and minus 40 ° C. The steps of r and z are nonuniform, the grid 62×200, the time

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step $\tau = 1$ sec. The problem of determining the non-stationary temperature field in a welded joint taking into account the phase transition in the temperature interval was solved numerically by the method of finite differences.

3. Results and discussion

Let us consider the process of cooling the welded joint. Figure 3 demonstrates the temperature distribution in the pipe wall at the cooling moment of 30 sec. at various ambient temperatures. An isoline limited by an isotherm of 80 °C serves as the boundary of the heat affected zone, which is calculated at the minimum and maximum acceptable air temperatures (figure 3a, 3b). It has been found that the boundary formed after the heating with duration according to the normative documents at an air temperature of -40 °C (figure 3c). HAZ boundary is formed beyond the permissible HAZ at heating of the ends during the period recommended at the minimum of the acceptable temperature is performed at AA temperature below the standard. Herewith, the period of its formation is significantly reduced. Such a rapid formation of the HAZ can affect the strength of the welded joint.

It is assumed that the preheating for welding has been accomplished according to the following parameters: the temperature of the heater is 60 °C, durations of heating and leveling are 30 and 100 sec., respectively, the length of the heated area is 3 cm [10]. Calculation reveals the temperature distribution $T_n(r,z)$, which is used as an initial condition in calculating the dynamics of the temperature field of welding pipes at low temperatures. Formation of the HAZ boundary at an AA temperature of -40 °C with preheating, leveling, welding both at permissible temperatures and using a heat-insulating structure (height - 2 cm, length - 2 cm) during the precipitation is shown in figure 3d.

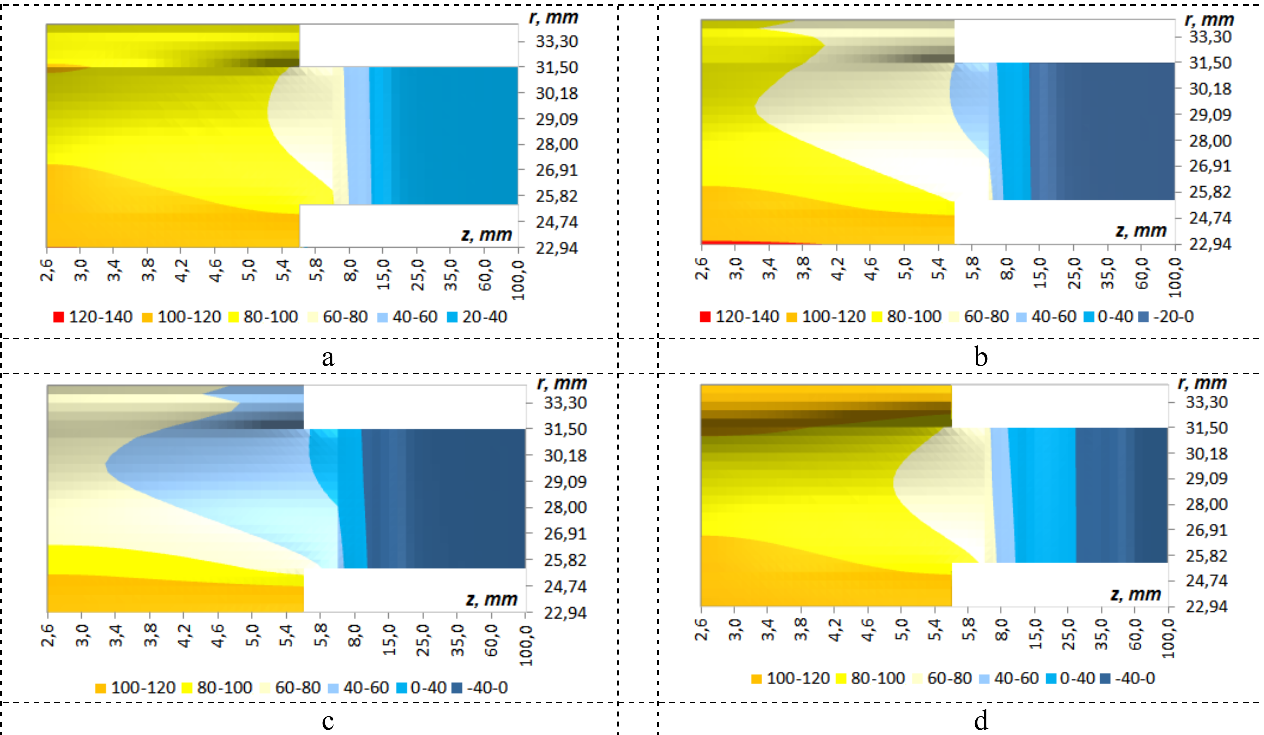

Figure 3. Temperature distribution in the pipe wall after fusion and junction of the welded pipe ends at different AA temperature at the cooling moment of 30 sec.: a) 30, b) -15, c) -40, d) -40 °C after preheating, temperature leveling and cooling in construction

Determination of the heat affected zone and the minimum time of its formation at acceptable AA temperatures allows us to assume that the required strength of welded joints is achieved by providing an acceptable HAZ boundary and the period of its formation when welding PE pipes at AA temperatures below the normative ones. Conducting the welding of polyethylene pipes with preheating and leveling the temperature, which is proposed in the present work, and cooling the welded joint in a heat-insulating structure with the dimensions calculated by the method described in [9] lead to an allowable cooling rate and to the formation of a quality weld at butt welding of polyethylene pipes at low temperatures.

4. Conclusion

The acceptable boundary of the heat affected zone, formed at permissible air temperatures and the time of its formation are calculated. Calculations show the possibility of providing an acceptable cooling rate for a welded joint and formation of HAZ in required boundaries at AA temperatures below the standard using a heat-insulating structure at the stage of upsetting of polyethylene pipes. The preheating, leveling and cooling of the welded joint in the heat-insulating structure are necessary conditions for the formation of a quality welded joint in the welding of polyethylene pipes at low temperatures.

5. References

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