Rapid welding technology for polyethylene gas pipes at temperatures below standard

N P Starostin¹, O A Ammosova²

¹Doctor of Technical Sciences, Head of Laboratory, Institute of Oil and Gas Problems
SB RAS, Yakutsk, Russia
²Candidate of Technical Sciences, Senior Researcher, Institute of Oil and Gas
Problems, SB RAS, Yakutsk, Russia

E-mail: oammosova@gmail.com

Abstract. Rapid polyethylene pipes welding technology at temperatures below standard is pro-
posed. This technology consists of preheating, equalization to acceptable temperature, reflow in regulated mode, and cooling under heat insulation layer or in heat-insulating chamber. Additional welding parameters, including heating and temperature equalization duration, heat-insulating layer thickness or heat-insulating chamber dimensions, are calculated from condition of ensuring heat process flow according to welding pattern at acceptable temperature. For mathematical model adequacy to actual heat welding process, it is proposed to consider polyethylene phase transformation heat in temperature range. When solving problem using end-to-end counting method, effective heat capacity coefficient is introduced, which is determined using temperature dependence of polymer material crystallinity degree. Crystallinity degree in welding process is determined by differential scanning calorimeter. Results of calculating cooling rates for polyethylene pipes electrofusion welding at various temperatures are given. Significant increase of cooling rate in heat-affected zone during welding at low temperatures, at which fine-crystalline structure is formed, which causes weld material plasticity, is shown. It is shown that when welding polyethylene pipes in low ambient temperatures, preheating, temperature equalization and cooling with thermal insulation with calculated parameters lead to thermal process in heat-affected zone according to welding patterns at acceptable temperature.

1. Introduction
Welding work during installation and repair of gas pipelines made of polyethylene pipes is recommended to be carried out at an ambient air (AA) temperature from minus 15 to 45 °C. At lower air temperatures, welding is recommended to be carried out in lightweight, heated structures with maintaining temperature in allowable range. At the same time, for welding, it is necessary to withstand the welded pipe sections for a long time for temperature control, which is unacceptable in emergency situations.

When welding polyethylene pipes at low temperatures during reflow process of welding surfaces, peripheral areas of welded joint are heated slightly due to low thermal conductivity of polymer material. In addition, at low AA temperature, convective heat transfer from free surfaces of the joint increases. These two factors contribute to increase in molecular heat transfer and increase in cooling rate in heat-affected zone (HAZ) at precipitation stage. It is known that at high rates of melt cooling,
crystal growth occurs slowly, and fine-crystalline structure is formed, which causes plasticity of polyethylene and low bonding strength [1].

In order to obtain welded joint at low temperatures, strength of which is not lower than during welding at conditions of permissible air temperatures, it is necessary to ensure that heat process in HAZ proceeds according to pattern, typical for welding at conditions of temperature from regulated range. Such temperature field dynamics can be obtained by preheating, reflowing in standard mode and cooling in a heat-insulating chamber or under a layer of heat-insulating material. When preheating, it is necessary to ensure close to uniform temperature distribution in permissible range by equalizing temperature. It is more effective to determine duration of heating and equalization of temperatures by calculation, simulating a non-stationary thermal process. Based on mathematical modeling, parameters of heat-insulating chamber or layer thickness of heat-insulating material are also determined. In mathematical modeling of heating and cooling of welded joint, it is necessary to consider absorption of heat during polymer material melting and its release during crystallization.

2. Mathematical model

It is known that polyethylene material for pipes has crystallinity degree of 55-65% [2]. When simulating thermal process in products made of polymeric materials, in order to consider heat of phase transformation, Avrami-Kolmogorov crystallization kinetics equation is usually used, the parameters of which are determined from DSC thermograms [3–5]. When developing technology of welding PE pipes at low temperatures, it is necessary to ensure cooling of product according to predetermined pattern of changes in the temperature field, without describing nucleation and growth of crystals. In this case, thermograms of differential scanning calorimeter (DSC) can be used directly for determination of phase transformation heat in mathematical model. In heat equation describing a non-stationary temperature field in welded joint, using shock-capturing method, an effective heat capacity coefficient is introduced [6]. The heat equation is written as:

\[
\begin{align*}
\left(c(T) + \rho L^{100\%} \right) \frac{dT}{dt} &= \text{div}(\lambda(T) \text{grad}T), \quad x \in D, \quad 0 < t \leq t_m, \tag{1}
\end{align*}
\]

where \(Q\) – heat source power; \(L^{100\%}\) – enthalpy of phase transition of completely crystalline polymer; \(X_C\) – degree of crystallinity; \(c(T) = \rho c^t + X_C(T) \left( \rho c^- - \rho c^t \right)\); \(\lambda(T) = \lambda^t + X_C(T) \left( \lambda^t - \lambda^t \right)\); \(c^-, \rho^-, \lambda^-\) and \(c^+, \rho^+, \lambda^+\) – specific heat, density and thermal conductivity for solid and liquid phases of pipe material, respectively.

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

\[
X_C(T) = \begin{cases}
X_C^t, & T \leq T_1, \\
\frac{T}{T_2 - T_1} \int_{T_1}^{T} q(u) du, & T_1 < T < T_2, \\
0, & T \geq T_2,
\end{cases} \tag{2}
\]

Here \(q(T)\) is the dependence of heat flux on temperature, referred to unit mass of substance, recorded by differential scanning calorimeter (DSC); \(X_C^t\) is the maximum degree of crystallinity of studied polymeric material; \(v_T\) is the temperature change rate.

Differentiating integral over variable upper limit in function (2), we have:
\[ \chi(T) = L^{100\%} \frac{dX_c}{dT} = \begin{cases} 0, & T \leq T_1, \\ \frac{-q(T)}{v_T}, & T_1 < T < T_2, \\ 0, & T \geq T_2, \end{cases} \] (3)

Then equation (1) is written as:

\[ (c(T) + \rho \cdot L^{100\%} \chi(T)) \frac{\partial T}{\partial t} = \text{div}(\lambda(T) \text{grad} T), \quad x \in D, \quad 0 < t \leq t_m, \] (4)

When welding parts with built-in heater, equation (4) is supplemented by condition of concentrated heat source. On other boundaries we have traditional boundary conditions. The non-stationary temperature field is determined by solving equation (4) with given initial and boundary conditions by the finite element method [7].

When butt welding with heating tool, temperature of the heating tool is set at welded ends of pipes. The task of determining temperature field is solved by the finite difference method [8].

Convective heat exchange \( \alpha \) at the contact of the pipe and the coupling with thermal insulation is determined from the expression [9]:

\[ \frac{1}{\alpha} = \frac{1}{\alpha_0} + \frac{h_{iz}}{\lambda_{iz}}, \] (5)

where \( h_{iz} \) is the thickness of the thermal insulation layer, \( \lambda_{iz} \) is the thermal conductivity of the insulation material, \( \alpha_0 \) is the heat exchange with the environment.

3. Data for calculations

The design scheme of pipe wall and coupling is presented in figure 1. Triangulation of computational domain \( D \) was performed using the Gmsh grid generator [10]. Problem (4) was solved by finite element method using free-access program Dolfin/FEniCS [11]. Visualization of results was implemented using the Paraview package [12].

![Figure 1. Design scheme: 1 - pipe wall; 2 - coupling wall.](image)

Simulation of temperature fields during electrofusion welding of polyethylene pipes was carried out for brand PE 100 GAZ SDR 11 63×5.8 at various ambient temperatures from +20 to -50 °C. Thermophysical properties of pipe and coupling material: thermal conductivities are \( \lambda^- = 0.46; \lambda^+ = 0.24 \text{ W/(m-K)} \); densities are \( \rho^- = 950; \rho^+ = 800 \text{ kg/m}^3 \); heat capacities \( c^- = 1900; c^+ = 2100 \text{ J/(kg-K)} \) [13]. 3. Data for calculations: \( r_1 = 0.0257 \) is inner pipe radius; \( r_p = 0.0315; r_{nuf} = 0.0397 \) is outer pipe radius.
and coupling radii, m; heating elements are located at radius $r_{up} = 0.0321$ m; $z_1 = 0.005$; $z_2 = 0.028$; $z_{wrf} = 0.046$; $z_tr = 0.09$ m. Spirals in coupling are made of copper: thermal conductivity $\lambda_{Al} = 238.2$ W/(m·K); density $\rho_{Al} = 2675$ kg/m$^3$; heat capacity $c_{Al} = 951.3$ J/(kg·K) [13]. There are 32 coils in the coupling. Welding voltage was taken to be $U = 32$ V; $R = 1.6$ Ω; $\beta = 4.30 \cdot 10^{-3}$ 1/°С. Duration of heating and cooling for standard welding at 20 °C is 70 seconds and 8 minutes, respectively.

4. Calculation results

Main idea of proposed approach lies in ensuring changes in temperature field close to dynamics, obtained at permissible air temperatures, in the area of welded sleeve joint, when welding polyethylene pipes at low ambient temperatures. According to calculations, at air temperatures below minus 15 °C, the size of melted zone decreases, which indicates smaller volume of melt produced (Figure 2). Size of heat-affected zone (HAZ), in which structural changes occur in welded materials, during heating and melting, has significant effect on formation of welded joint. Usually, HAZ is determined experimentally by examining structural indicators. Let us take commonly used assumption that structural changes occur at temperatures above softening temperature of material. Mathematically, task is reduced to finding the curve farthest from the welded joint, at each point of which maximum temperature is reached equal to material softening temperature of 80 °C.

![Temperature Distribution](image)

a

b

c
In order to increase depth of penetration at air temperatures below minus 15 °C, it is proposed to carry out preheating and leveling prior heating. Preheating of welded surfaces of pipe and coupling is performed using heating spiral of coupling. Further, leveling is carried out to establish more uniform temperature field in coupling and pipe. Duration of heating and leveling, as well as power supplied to the voltage spiral, are determined by calculation. In order to maintain required cooling rate, outer surface of coupling with pipe is covered with insulating material. Thickness of covering material is determined by calculation.

The quality of welded coupling connection is significantly influenced by cooling rate of material. Figure 3 shows the time dependences of temperatures during cooling of welded joint for 8 minutes at various ambient temperatures.

Cooling rate at temperature of 20 °C (curve 1), in the range of 120–115 °C is \( V_{120-115} = 25 \) °C/min, in the range of 115–110 °C \( V_{115-110} = 7 \) °C/min, in the range of 110–105 °C \( V_{110-105} = 5 \) °C/min, in the range of 105–100 °C \( V_{105-100} = 8 \) °C/min, in the range of 100–95 °C (interval in which intensive crystallization occurs) \( V_{100-95} = 10 \) °C/min. Note that the rate of \( V_{100-80} = 10 \) °C/min lasts until the end of the crystallization process.
At AA temperature of minus 15 °C (lower limit of AA temperatures allowed for welding without using light heated shelters) cooling rates are: $V_{120-115}=40$, $V_{115-110}=13$, $V_{110-105}=10$, $V_{105-100}=14$, $V_{100-95}=20$, $V_{95-90}=18$, $V_{90-85}=17$, $V_{85-80}=16$ °C/min (curve 2).

At AA temperature of minus 50 °C welding without heating and cooling without heat insulation leads to significant decrease in temperature ($V_{120-115}=85$, $V_{115-110}=33$, $V_{110-105}=26$, $V_{105-100}=37$, $V_{100-95}=46$, $V_{95-90}=40$, $V_{90-85}=33$, $V_{85-80}=28$ °C/min) and temperature distribution curves lie outside allowable range of temperature variations (curve 3).

At low temperature conditions, the use of preheating and heat-insulating chamber with wall thickness of 2 cm results in cooling rate at crystallization stage, that is characteristic for welding at acceptable AA temperature (curve 4).

5. Conclusion
- When welding polyethylene pipes PE 100 GAZ SDR 11 63×5.8 at permissible ambient temperatures, cooling rate of weld material in range 115-120 °C is 25, in range 85-115 from 5 to 10 °C/min. When welding at minus 50 °C, cooling rate of weld, corresponding to the same temperature ranges, is 85 and from 28 to 46 °C
- When electrofusion welding of polyethylene pipes, preheating is performed using built-in heater with subsequent temperature equalization with estimated duration, melting in regulated mode and cooling under insulation layer of calculated thickness leads to cooling of weld material at speed that guarantees high-quality weld.

Acknowledgments
The research was carried out within the state assignment of FASO of Russia (project No. AAAA-A17-117040710038-8 dated April 7, 2017).

References
[1] Kaygorodov G K and Kargin V Yu 2001 Truboprovody i ekologiya 2 13–14
[2] Gorilovskiy M, Kalugina E, Ivanov A and Satdinova F 2005 Plasticheskie massy 4 9–12
[3] Chebbo Z, Vincent M, Boujlal A, Gueugnaut D and Tillier Y 2015 Polym. Eng. Sci. 55 123–31
[4] Spina R, Spekowius M and Hopmann C 2018 Thermochim. Acta 659 44–54
[5] Kulikova T and Trufanov N 2008 Vychislitelnaya mehanika sploshnykh sred 1(2) 38–52
[6] Samarskiy A A and Vabischevich P N 2004 Vychislitelnaya teploperedacha (Moscow: Editorial URSS) p 784
[7] Abedian A, Parvizian J, Düster A and Rank E 2014 Appl. Math. Mech. 35(10) 1239–1248
[8] Samarskii A A 2001 The theory of difference schemes (New York: Basel. Marcel Dekker Inc)
[9] Isachenko V P, Osipova V A, Sukomel A S 1969 Heat Transfer (Moscow: Energija) p 440
[10] Software GMSH. URL: http://geuz.org/gmsh/
[11] Logg A, Mardal K A and Garth N 2011 Wells Automated Solution of Differential Equations by the Finite Element Method. The FEniCS Book
[12] Software package PARAVIEW. URL: http://www.paraview.org/
[13] A P Babichev, N A Babushkina, A M Bratkovskiy and etc. 1991 Fizicheskie velichiny Spravochnik ed I S Grigoreva and E Z Meyltkhova (Moscw: Energoatomizdat) p 1232