Considering Phase Transformation Heat When Modeling Thermal Process of Polyethylene Pipes Welding

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Abstract. Mathematical modeling of heat process, considering phase transformation heat, is used to develop technology of welding polyethylene pipes with built-in heating elements at low outdoor temperatures. Mathematically, task is to control technological parameters of welding in order to ensure flow of thermal process at low temperatures according to consistent patterns of welding at acceptable temperatures. With this control of thermal process, the need of ensuring certain sizes of supramolecular structures is eliminated, which allows us to simplify accounting for phase transformation heat. Instead of traditionally used crystallization kinetics equation, it is proposed to directly use differential scanning calorimeter (DSC) data to ensure given temperature field dynamics. Since during phase transformation heat is released and absorbed only by crystalline part of polymer material, special role is assigned to function of crystallinity degree. Formula is given for determining the effective heat capacity coefficient used in the shock-capturing method for solving heat conduction problem with phase transition in temperature range, based on temperature dependence on crystallinity degree. The calculation results for pipes with diameter of 63 mm at various ambient temperatures are shown. Significant increase in cooling rate at air temperatures below minus 15 ° C has been shown.

1. Introduction

In regions of cold climate, during construction and repair of gas pipelines from polyethylene pipes, as well as water supply systems from polypropylene pipes, it is often necessary to carry out welding work at ambient air (AA) temperatures below standard. Welding at temperatures below standard is recommended to be carried out in shelters in which temperature is maintained in permissible range of minus 15 to +40 ° C. To obtain high-quality welded joint, it is necessary to thermostat welded ends of pipes for a long time, which is unacceptable in emergency situations and at carrying out large amount of welding work. To develop methods for efficient welding of polymer pipes at low temperatures, it is necessary to control heat process [1]. Since experimental study of thermal process of welding in wide range of air temperatures for various pipe sizes is almost impossible, it is more efficient to implement thermal process control using mathematical model of temperature field dynamics in welded joint. With this approach, successful management of thermal process largely depends on adequacy of mathematical model to real process. The most difficult in modeling thermal process of welding is to consider phase transformation heat.
2. Relevance
For certainty, we will consider welding of polyethylene pipes. It is known that polyethylene material for pipes has crystallinity degree of 55-65% [2]. When melting and hardening, amorphous substance does not absorb and does not release heat. Therefore, during phase transformation of polyethylene, it is necessary to consider the heat absorbed and emitted only in the crystalline part.

In many works devoted to simulation of thermal process in products from polymeric materials with phase transformations, Avrami-Kolmogorov crystallization kinetics equation is used, parameters of which are determined from DSC thermograms [3–4]. Such approach is justified if it is necessary to consider the nucleation and growth of crystals when modeling and allows us to associate macromodel of thermomechanical behavior of material with micromodel of crystallization kinetics [5–7]. In the case when nucleation and growth of crystals are of secondary importance or it is necessary to ensure specified change in temperature field during cooling of product, as in development of welding technology at low temperatures, it is more efficient to directly use heat flux functions recorded by DSC. Such approach to considering phase transformation heat using relative crystallinity function was used in development of technology of butt welding at low temperatures. When using function of relative crystallinity, it is considered that polymer material is completely crystalline, which in some way distorts the results of calculations of dynamics of temperature fields.

In this paper, we propose to use function of crystallinity degree, which depends on temperature, when modeling thermal process of welding polymer pipes, considering phase transformation heat.

3. Problem formulation
Computational domain and grid of pipe wall and coupling are presented in Figure 1. Non-stationary temperature field in welded joint, considering phase transformation heat, is described by heat equation with effective heat capacity coefficient [8–9]:

\[
\left( c(T) + \rho^\ast L_1^{100} \frac{dX_C}{dT} \right) \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda(T) \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda(T) \frac{\partial T}{\partial z} \right) + \frac{Q(T)}{n \cdot 2 \pi r} \delta(r - R_{wp}) \sum_{i=1}^{n} \delta(z - z_i), \quad r, z \in \Omega, \; 0 < t \leq t_m, \tag{1}
\]

where \( Q \) – heat source power; \( L_1^{100} \) – specific heat of phase transformation of completely crystalline polymer; \( X_C \) – crystallinity degree; \( c(T) = c^\ast + X_C(T) \cdot \left( \rho^+ c^+ - \rho^- c^\ast \right) \); \( \lambda(T) = \lambda^\ast + X_C(T) \cdot \left( \lambda^\ast - \lambda^+ \right) \); \( c^\ast, \rho^\ast, \lambda^\ast \) и \( c^+, \rho^+, \lambda^+ \) – specific heat capacity, density and thermal conductivity for solid and liquid phases of pipe material, respectively; \( n \) – number of coils of heating element; \( z_i \) – axial coordinates of coils location; \( R_{wp} \) – winding radius of electric heating coil in coupling body; \( \delta \) – Dirac delta function.

Crystallinity degree \( X_C \) is determined by formula:

\[
X_C(T) = \begin{cases} 
  X_C^\ast, & T \leq T_1, \\
  \int_T^{T_2} q(u) du \over L_1^{100} \cdot \nu_T, & T_1 < T < T_2, \\
  0, & T \geq T_2, 
\end{cases} \tag{2}
\]
Figure 1. Computational domain (a) and grid (b): 1 – pipe wall; 2 – coupling wall.

Here \( q(T,\dot{\nu}_T) \) – dependence of heat flux on temperature and temperature change rate referred to unit mass of substance, recorded by differential scanning calorimeter (DSC); \( X_c^\infty \) – the maximum degree of crystallinity of the studied polymeric material; \( \nu_T \) – temperature change rate.

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

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

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

\[
\left[(c(T) - \rho \chi(T))\frac{\partial T}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda(T) \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda(T) \frac{\partial T}{\partial z} \right) + \frac{Q(T)}{n \cdot 2\pi r} \sum_{i=1}^{n} \delta(z - z_i), \ (r, z) \in \Omega, \ 0 < t \leq t_m, \right]
\]

Equation (4) is supplemented by initial condition:

\[
T(x,0) = T_0, \ (r, z) \in \Omega.
\]

We set boundary condition of third kind on the outer surface of pipe, which describes heat exchange with air [10]:

\[
-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_0), \ (r, z) \in \Gamma_1.
\]

On left border of considered domain, symmetry condition is satisfied:
\[-\lambda \frac{\partial T}{\partial n} = 0, \ (r, z) \in \Gamma_2,\]

On right – condition of first kind:
\[T = T_0, \ (r, z) \in \Gamma_3\]

where \(T_0\) – ambient air temperature, \(\alpha\) – coefficient of convective heat exchange with air.

The proposed approach for describing temperature field dynamics during welding considers phase transformation heat using DSC data and function of crystallinity degree. The usage of crystallinity degree function allows to consider that polyethylene partially crystallizes, and fraction of crystalline part does not exceed the limiting value \(X_C^\infty\).

The power of the heat source was calculated by formula:
\[Q(t) = \frac{U^2}{R \cdot (1 + \beta(T - 20))}\]

where \(R\) – resistance of electric heating coil at temperature 20 °C; \(\beta\) – temperature coefficient of resistance.

Problem (4) - (9) was solved by finite element method [11–13]. For numerical solution, open library FEniCS was used [14–15]. Triangulation of computational domain was performed using the Gmsh grid generator [16]. Visualization of results was implemented using the Paraview package [17].

Simulation of temperature fields during electrofusion welding of polyethylene pipes was carried out for grade PE 100 GAZ SDR 11 63×5.8 at various ambient temperatures from +20 to minus 50 °C. Thermophysical properties of material of pipe and coupling: coefficients of thermal conductivity \(\lambda = 0.46; \lambda^* = 0.24\) W/(m-K); coefficients of density \(\rho = 950; \rho^* = 800\) kg/m³; coefficients of heat capacity \(c^* = 1900; c^* = 2100\) J/(kg-K) [18]. Data for calculation: \(r_{pi} = 0.0257\) inner pipe radius; \(r_p = 0.0315; r_c = 0.0397\) – outer radius of pipe and coupling, m; heating elements are located at radius \(r_{he} = 0.0321\) m; \(z_r = 0.005; z_i = 0.028; z_c = 0.046; z_p = 0.09\) m. Coils in coupling are made of copper: thermal conductivity \(\lambda_{cu} = 238.2\) W/(m-K); density \(\rho_{cu} = 2675\) kg/m³; heat capacity \(c_{cu} = 951.3\) J/(kg-K) [18].

Number of coils in coupling is 32. Welding voltage was taken equal \(U = 32\) V; \(R = 1.6\) Ohm; \(\beta = 4.30 \cdot 10^{-3}\) 1/°C. Duration of heating and cooling for standard welding at 20 °C is 70 seconds and 8 min, respectively.

4. Results and discussion

Structural changes in polymeric materials occur at temperatures above softening temperature, for polyethylene it is 80 °C. Calculations showed reducing of melted zone with decrease in ambient temperature. Figure 2 (a) shows temperature distribution over radius after finishing melting at various ambient temperatures. According to calculations, width of melted zone at air temperature minus 15 °C (minimum allowable temperature for welding) was 8.5 mm, and at temperature of minus 40 °C, the width of reflow zone was only 5.5 mm. Reducing the width of melted zone by more than 30% leads to smaller volume of resulting melt, which leads to insufficient pressure of welded surfaces, more intensive crystallization and formation of fine-crystalline structure of welded joint material. Calculation results show the need for preheating when welding PE pipes at low ambient temperatures. Calculations also established the need to use thermal insulation. At low air temperatures, preheating, equalization, heating and cooling the welded joint under thermal insulation layer leads to formation of dimensions of melted zone close to zone obtained at permissible air temperatures.

Proposed technology of electrofusion welding of polyethylene pipes at air temperatures below standard includes following operations: preheating, equalization, heating, cooling under layer of thermal insulation. Preheating of the heat-affected zone is carried out via embedded heating element of connecting electrofusion coupling. Then temperature is equalized by free cooling to temperature
acceptable for welding. Heating (reflow) according to regulated welding mode with imitation of ambient air temperature sensor of average temperature in heat-affected zone after equalization. Cooling of welded joint under heat insulation layer.

In order for calculating scheme to remain the same when changing thickness of insulation on outer border of coupling and part of the pipe, effective heat transfer coefficient $\alpha_{ef}$ is introduced (boundary $\Gamma_{in}$), value of which depends on coefficient of heat exchange with air $\alpha$, thickness $h$ and thermal conductivity $\lambda_{in}$ of used thermal insulation material [19–20]:

$$\frac{1}{\alpha_{ef}} = \frac{1}{\alpha} + \frac{h}{\lambda_{in}}.$$  \hfill (10)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{(a) – temperature distribution over radius at the moment of melting completion; (b) – time dependences of temperatures when cooling welded joint for 8 minutes at various AA temperatures: 1 – 20; 2 – minus 15; 3 – minus 40; 4 – minus 40 °C (heating, equalization, cooling under insulation).}
\end{figure}
Next, consider the cooling process in which weld is formed. Figure 2 (b) shows temperature distribution at cooling stage at various ambient temperatures at certain point at slight distance from the coil. At permissible AA temperatures of -15 and 20 °C, cooling is carried out without thermal insulation (curves 1–2). At AA temperature of -40 °C no pre-heating and cooling without heat insulation leads to significant decrease in temperature and temperature distribution curve lies outside permissible range of temperature changes (curve 3). When using thermal insulation with thickness of 2 cm (curve 4) and preheating and leveling prior to melting, temperature distribution curve lies in allowable corridor, and dynamics and flow of heat process correspond to constant patterns and to temperature changes during welding at allowed welding AA temperatures.

5. Conclusion

Proposed method of considering phase transformation heat can be used to determine additional welding parameters at low temperatures, including duration of heating and temperature equalization, thickness of layer of insulating material.

References

[1] Ammosova O A and Starostin N P 2018 IOP Conf. Ser.: Mater. Sci. Eng. 463 022069
[2] Gorilovskiy M I, Kalugina E V, Ivanov A N and Satdinova F K 2005 Plasticheskie massy 4 9–12
[3] Kulikova T G and Trufanov N A 2008 Vychislitelnaya mekhantika sploshnykh sred 2 38–52
[4] Chebbo Z, Vincent M, Boujilal A, Gueugnaut D and Tillier Y 2015 Polym. Eng. Sci. 55 123–31
[5] Spina R, Spekowius M and Hopmann C 2018 Thermochim. Acta 659 44–54
[6] Spina R, Spekowius M and Hopmann C 2016 Mater. Des. 95(5) 455–469
[7] Rong Y, He H P, Cao W, Shen C Y and Chen J B 2013 Comput. Mater. Sci. 67 35–39
[8] Samarskii A A 2001 The theory of difference schemes (New York: Basel, Marcel Dekker Inc)
[9] Samarskiy A A and Vabischevich P N 2004 Vychislitelnaya teploperedacha (Moscow: Editorial URSS) p 784
[10] Pavlov A V, Perlshteyn G Z and Tipenko G 2010 Kriosfera Zemli 1 3–12
[11] Hughes T J 2012 The finite element method: linear static and dynamic finite element analysis (New York: Dover Publications)
[12] Zienkiewicz O C, Taylor R L and Zhu J Z 2005 The Finite Element Method: Its Basis and Fundamentals (Burlington: Butterworth-Heinemann)
[13] Zienkiewicz O C and Taylor R L 2000 The Finite Element Method: Solid Mechanics (Burlington: Butterworth-heinemann)
[14] Logg A, Mardal K A and Wells G N 2012 Automated Solution of Differential Equations by the Finite Element Method. The FEniCS Book (Heidelberg: Springer) p 723
[15] Software package FEniCS http://fenicsproject.org/
[16] Software GMSH http://geuz.org/gmsh/
[17] Software package PARAVIEW http://www.paraview.org/
[18] Babichev A P, Babushkina N A, Bratkovskiy A M and etc. 1991 Fizicheskie velichiny Spravochnik ed I S Grigoreva and E Z Meyltkhova (Moscow: Energoatomizdat) p 1232
[19] Isachenko V P, Osipova V A and Sukomel A S 1969 Heat Transfer (Moscow: Energiiya) p 440
[20] Lykov A V 1971 Teplomassoobmen Spravochnik (Moscow: Energiiya) p 560

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