BUTT-WELDING POLYETHYLENE PIPE AT LOW AMBIENT TEMPERATURES, THERMAL PROCESSES

GRAMA Lucian, POP Cosmin, GABOR Marius
University of Oradea, The Faculty of Management and Technological Engineering,
decanat_fei@uoradea.ro, 410087 Oradea, Bihor, Romania, 1, Universitatii street,
Tel/Fax:+40 259/408100, Tel:+40 259/408104; +40 259/408204

Key words: Butt-Welding, Pipes, Polyethylene

1. INTRODUCTION

In butt-welding polymer pipe, the deformation of the material, the change in supermolecular structure,the melt flow, solidification, stress relaxation, and other processes are the consequence of thermal and mechanical factors affecting the formation of a high-quality weld joint. When the ambient temperature T am is between –15and 45 C, we know the welding parameters that ensure the required long-term strength of the weld seam. The recommended parameter values are included in the relevant standards . The temperature variation of the pipe wall during welding at the permissible Tam is known as the permissible temperature-field dynamics. In welding polyethylene pipe when T am is below the standard values, welding in light structures is recommended. However, such welding is associated with wasteful energy expenditures and prolonged preparation, which is unacceptable in emergencies. It is important to develop welding methods for polyethylene pipe in cold regions during winter, when Tamis below –15°C.

Essentially, our proposal is that, during the buttwelding of polyethylene pipe at low temperature, efforts be made to ensure a thermal process closely resembling the permissible temperature-field dynamics in the region of pipe wall where structural changes occur. Then, the parameters of the external mechanical factors (the pressure in melting of the ends and setting, the setting rate, the holding time under pressure) may be taken from the standard documents.

Mathematical simulation permits the most complete investigation of the thermal process in welding polymer pipe. In most cases, this thermal process is investigated by means of the one-dimensional heat-conduction equation . The fact that some of the molten material is squeezed out during setting and forms burring is generally disregarded, as is the shortening of the welded pipe. In the present work, the mathematical simulation of the thermal process in welding polyethylene pipe takes account of burring. On the basis of the results, the welding parameters that correspond to permissible temperature-field dynamics are determined.

2. MATHEMATICAL MODEL

Determination of the nonsteady temperature field in the pipe wall at the melting stage reduces to solving the following system of equations:

$$c_i(T)\rho_i(T)\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_i(T)\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_i(T)\frac{\partial T}{\partial z}\right), \qquad (1)$$

$$0 < t \le t_m, \quad 0 < r < r_2, \quad 0 < z < l,$$

where c(T) is the specific heat of the pipe material, J/kg K;ρ(T) is the density, kg/m 3; λ (T) is the thermal conductivity,W/m K;tmis the calculation time;r,zare cylindrical coordinates.

Subscript i= 1 corresponds to solid pipe material; i= 2 to liquid pipe material; and i = 3 to the surrounding air. The initial temperature distribution in the pipe is uniform; its temperature is equal to the ambient temperature T am.

$$T(r, z, 0) = T_{\mathrm{am}}. \qquad (2)$$

At one end, the heating-element temperature Th is specified during heating

$$T(r, 0, t) = T_{\mathrm{h}}, \qquad (3)$$

and the absence of a heat flux (symmetry of the temperature field) is specified during cooling

$$\left.\frac{\partial T}{\partial z}\right|_{z=0} = 0. \qquad (4)$$

Taking account of the low heat conduction of polyethylene, we assume that, at some distance from the welding zone, the pipe temperature is constant throughout the process. Thus, at the other end of the pipe, we specify the condition

$$T(r, l, t) = T_{\mathrm{am}}. \qquad (5)$$

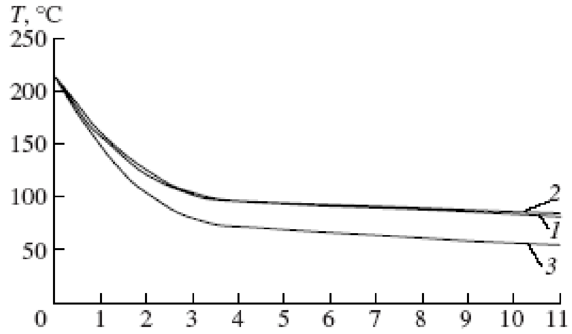

Fig. 1. Temperature distribution over pipe length l: 1) t = 55 s at Tam = 20□C; 2) t = 110 s at Tam = –40□C; 3) t = 55 s at Tam = –40□C.

When r = 0, we specify the natural condition that the solution is finite

$$\lim_{r \to 0} \lambda_3 r \frac{\partial T}{\partial r} = 0. \qquad (6)$$

At the outer surface of the pipe, convective heat transfer with the surrounding air will occur

$$\lambda_1 \left.\frac{\partial T}{\partial r}\right|_{r=r_2} = -\alpha[T(r_2, z, t) - T_{\mathrm{am}}]. \qquad (7)$$

At the melting boundary, we write the Stefan condition

$$(\lambda_1 \mathrm{grad}\, T - \lambda_2 \mathrm{grad}\, T, \mathrm{grad}\, \Phi) - Q_{\Phi} \Big| \rho \frac{\partial \Phi}{\partial t} = 0, \quad (8)$$

Where Φ(r,z,t) is the equation of the phase-boundary position at time t;QΦis the specific heat of phase transition. The problem in Eqs. (1)–(8) is solved by the coeffi-cient-smoothing method [3]. The computational algorithm is constructed by means of purely implicit schemes. The resulting nonlinear three-point equations are solved by the iterative method; the solution at each iteration is found by fitting [4].

3. CALCULATION RESULTS

The following data are assumed in the calculations: r1= 0.0257; r2= 0.0315; l= 0.1 m;λ1= 0.46; λ2= 0.24; λ3= .0338 W/m K;ρ1= 950; ρ2= 800; ρ3= 1.2 kg/m3;c1= 2000;c2= 2400;c3= 1007 J/kg K;TΦ= 128°C on melting and TΦ= 111°C on cooling;QΦ= 157 kJ/kg;Δ= 10°C [5].Analysis of the temperature distribution over the length l of the pipe at different times (Fig. 1) shows that,at the melting stage, the temperature fields in the pipewhen Tam is below the standard values (–40°C, say) and when Tam = 20°C will come to resemble one another if the heating time is increased.

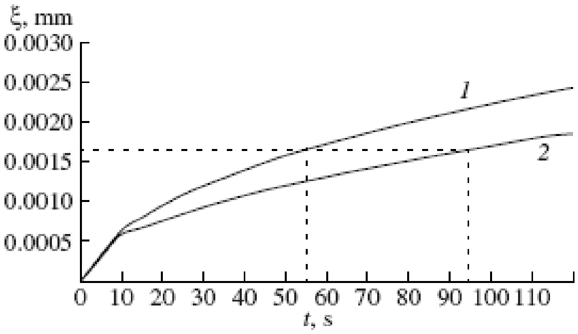

Fig. 2. Variation in melting depth at T_{am} = 20°C (*1*) and –40°C (*2*).

The contact time of the heating tool and the edge of the pipe is selected so as to ensure a particular melting depth ξ. Recommended melting times for the ends of low-pressure polyethylene pipe of different wall thicknessmay be found in [1]. For instance, in welding PE 60 GAZ SDR11 63 x̧ 5.8 polyethylene pipe (State Standard GOST R 50838–95), the recommended melting time innormal conditions is 55 s, while the calculated melting depth is 1.63 mm. According to calculations, the same melting depth may be obtained in melting for 96 s when Tam = –40°C (Fig. 2). As a result, the temperature fields in the regions considered are practically the same. Neglecting the technological delay and the flow time of the melt in setting, we may assume that the shortening of the pipe is equal to the shrinkage. To simplify the calculations, we assume that the cross section of the burring is rectangular. For 2.6-mm shrinkage, the cross section takes the form of a square with 3-mm sides. The coordinate origin is shifted over the length of the pipe by the amount of the shrinkage and set at the pipe junction.At the beginning of cooling, the temperature distribution of the burring is assumed to be uniform, while the temperature of the burring is determined from the thermal-balance condition: the heat in the material that is displaced to the burring is equal to the heat in the burring. Thus, the temperature distribution in the pipe with burring at the beginning of cooling is obtained by determining the temperature field at the end of melting. Although the technological delay is neglected in the calculations, we assume that, when the heating tool is removed from the pipe to be welded and the molten parts are pressed together, the air temperature within the pipe becomes equal to the ambient temperature and then increases on account of heat transfer from the hot section of the pipe at the cooling stage. The dynamics of the temperature field at the wall and within the pipe on cooling is determined by solving the Stefan problem. Conditions of convective heat transfer with the surrounding air are specified at the free surface of the burring; and symmetry is specified at the end of the pipe. The influence of the burring on the weld-joint temperature may be established by simulating the cooling of pipe without burring, taking account of the shrinkage.Initially, the appearance of burring increases the temperature.

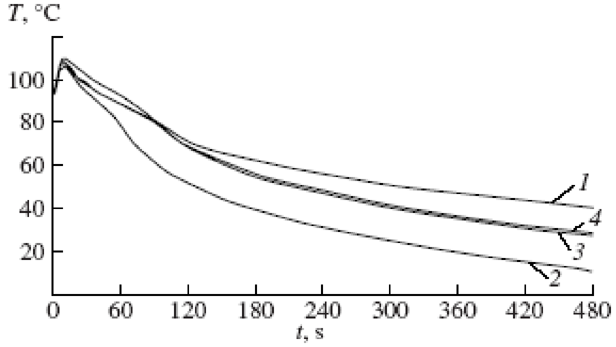

Fig. 3. Dependence of temperature T on time t at a point of the pipe ($r = 0.0315$; $z = 0.001$) when $T_{am} = 20$ (*1*), –15 (*2*), and –40°C with ideal insulation over the whole of the pipe (*3*) and a segment (*4*).

Then the temperature falls. The cooling rate has two peaks, corresponding to the time delay of the thermal influence of the burring on the pipe's inner and outer surfaces. After about 45 s, the cooling rate at the given point obtained when the burring is taken into account exceeds the cooling rate obtained without burring. Subsequently, the curves asymptotically converge, indicating that the thermal influence of the burring attenuates over time. However, this influence is signifi- cant in the portion of the cooling period governed by the standard documents. Thus, in selecting the welding conditions, the mathematical model of the thermal process must include the influence of burring on the temperature- field dynamics. We now investigate the temperature dynamics in the weld joint of polyethylene pipe during melting on the assumption that convective heat transfer occurs at the external pipe surfaces with burring at the permissible welding temperatures Tam = [–15, 45]°C, whereas these surfaces are ideally heat-insulated at lower temperatures. The calculations show that, on cooling the weld joint at low Tam, the air temperature within the pipe reaches a maximum after a few seconds and then gradually declines and varies within the permissible ambient temperatures in the course of cooling.

This indicates that, at naturally low ambient temperatures, there will be convective heat transfer of the internal pipe surface with the air close to the joint, at temperatures that are permissible in welding. This is also the case at distances of 2 cm from the joint. Ideal heat insulation of the outer pipe surface on welding at low ambient temperatures reduces the cooling rate of the weld joint in the period between 30 and 90 s from the instant that the pipes are pushed together.The temperature varies in the range from 100 to 80□C, where intense phase transition occurs in polyethylene. Consequently, a large-grain crystalline structure may be formed, increasing the likelihood of brittle failure in the polyethylene [6].

However, with no heat insulation of the external surface, the cooling rate increases at low ambient temperatures, and solidification may be interrupted at an intermediate stage. In structure formation with slow cooling, by contrast, the disintegrating crystallization centers may be restored [7].

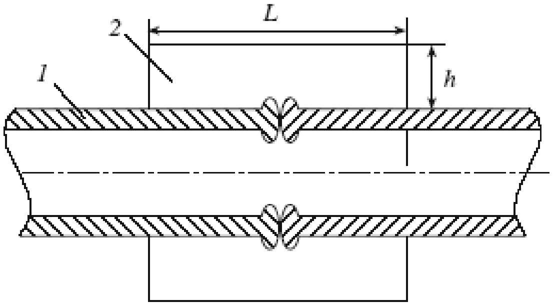

Fig. 4. Heat-insulation chamber: 1) polyethylene pipe; 2) heat-insulation chamber.

Therefore, there is an intermediate condition such that cooling of the weld joint will occur in the same way as at permissible ambient temperatures. This condition may be created by partial heat insulation of the external pipe surfaces.

Calculations show that the time dependence of the temperature in the pipe is practically changed if ideal heat insulation only applies in the hotter section of the pipe, and convective heat transfer occurs elsewhere. For example, if a section of pipe measuring 2 cm from the weld joint is ideally insulated, the corresponding time dependence of the temperature coincides with the corresponding curves for heat insulation over the whole outer surface of the pipe (Fig. 3).

Hence, the cooling rate in the region of structural changes may be regulated by heat insulation of the section of pipe around the weld seam. For this purpose, we propose the cylindrical heat-insulation chamber in Fig. 4. The chamber dimensions are determined on the basis of simulation of weldjoint cooling inside a heat-insulation chamber, so as to ensure a permissible cooling rate.

Simulation of the cooling of welded pipe in the presence of a heat-insulation chamber is based on the solution of the Stefan problem. We assume that a uniform air temperature within the chamber is established relatively rapidly (within a single time step of the calculation). Suppose that the present value of the air temperature in the chamber is known. In the next time step, the air temperature in the chamber Tch(t) is determined on the basis of the thermal balance, taking account of the convective heat transfer with the surface of the pipe and burring in a chamber filled with air at a known temperature Tch(t)

$$Q = \alpha \int_{\Gamma} (T|_{\Gamma} - \check{T}_{ch}(t))\tau \, d\Gamma, \qquad (9)$$

where Q is the quantity of heat; Γ is the external surfaceof the pipe and burring bounded by the chamber; α is he heat-transfer coefficient with the outer surface of the pipe and burring. On account of the heat Q, the temperature in the chamber rises, according to the relation

$$Q = c_3 \rho_3 V_{ch}(T_{ch} - \check{T}_{ch}),$$

where Vch is the chamber volume.

The mean temperature in the chamber obtained by calculation depends on the geometric dimensions.

Calculations show that increasing the chamber length, with fixed height, reduces the internal temperature; this corresponds to physical concepts. Increasing the chamber length increases not only the chamber volume but also the surface of the pipe at lower temperature, thereby reducing the temperature in the chamber. However, increasing the chamber height (radius), with fixed length, also reduces the air temperature within the chamber, but not as markedly.

Therefore, to facilitate manufacture and practical use of the heat-insulation chamber, one of its dimensions—say, the height—may be fixed, and the chamber length may be varied so as to identify the value corresponding to permissible cooling rate of the weld joint. When the chamber height is 0.02 m, the chamber half-length L/2 = 0.02 m ensures a permissible cooling rate at low ambient temperatures between –45 and –15°C.

Characteristic time dependences of the temperature on cooling the weld joint in a heat-insulation chamber at various Tam are shown in Fig. 5. For comparison, the limiting curves at Tam = –15 and 45°C on natural cooling are also shown, as well as the temperature variation in natural cooling when Tam = –40°C. The time dependence of the temperature on cooling in a heat-insulation chamber lies between the limiting curves. In addition, each temperature curve obtained on cooling the weld joint in the chamber corresponds to a curve obtained in natural cooling for some Tam from the permissible range. Calculations show that cooling of the near-seam zone of the joint in the heat-insulation chamber at Tam = –40°C, say, corresponds to natural cooling at Tam = 0°C.

When a chamber of the given size is used, there is no slowing of the cooling rate in the region of structural changes, in contrast to the case with ideal heat insulation of the pipe's outer surface. Hence,in the vicinity of the weld seam, the structure of the material will be the same as in welding at permissible ambient temperatures.

However, when Tam = –50°C or less, the proposed chamber dimensions do not ensure the required cooling rate. Therefore, we may consider reducing the chamber length. Calculations show that, when L/2 = 1.5 cm, the required cooling rate is obtained. It is also found that chamber dimensions L = 3 cm and h = 2 cm ensure the permissible cooling rate when Tam is between –45 and –60°C. Note that the use of such a chamber to cool the weld joint at ambient temperatures between –45 and –15°C leads to extreme decrease in the cooling rate in the interval between 30 and 90 s after the pipes are pressed together, as in ideal heat insulation.

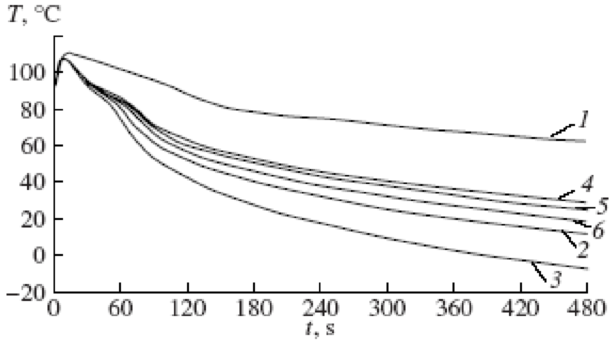

Fig. 5. Dependence of temperature T on time t at a point of the pipe ($r = 0.0315$; $z = 0.001$) when $T_{am} = 45$ (1), −15 (2), −20 (4), −30 (5), and −40°C (6), with (4–6) and without (1–3) a heat-insulation chamber.

4. CONCLUSIONS

On the basis of mathematical simulation of the thermal process, we have proposed and verified a method of determining the melting time when polyethylene pipe is welded at below-standard ambient temperatures.

A method has been outlined for calculating the nonsteady wall-temperature field in welding polymer pipe, taking account of the latent heat of phase transition and the thermal influence of burring. The determination of appropriate dimensions for the heat-insulation chamber in the cooling stage has been described.

After successful testing, the proposed methods may be used to determine the parameters corresponding to permissible temperature- field dynamics in welding polyethylene pipe when the ambient temperature is below the standard range.

5. REFERENCES

[1] Alamoreanu E., Chirita R., “Bare si placi din materiale composite”, Editura Tehnica Bucuresti 1997;
[2] Amza Gh. s.a., “Tratat de tehnologia materialelor”, Editura Academei Romane, Bucuresti 2002;
[3] Benatar A., “Ultrasonic welding of advaced thermoplastic composites”, Massachusetts Institute of Tehnology, 1987 USA;
[4] N. P. Starostin, O. A. Ammosova., “Thermal Processes in Butt-Welding Polyethylene Pipe”, Vestnik Mashinostroeniya, 2009, No. 1, pp. 17–20;