Polymer Testing 31 (2012) 557–563

Contents lists available at SciVerse ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Property modelling

Experimental and numerical investigation of barreling at the cut ends of solid and skinned PE pipes

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ARTICLE INFO

Article history:
Received 10 January 2012
Accepted 25 February 2012

Keywords:
PE pipes
Electrofusion
Barreling
Residual stresses

ABSTRACT

When a thermoplastic pipe is cut to length, residual stresses frozen in during cooling are released, causing local bending which reduced the diameter of the pipe at the cut end. Moving back inwards from the cut end, the measured pipe diameter does not simply increase to its initial value but locally overshoots to a new maximum, giving the end of the pipe a 'barrel' shape that can be inconvenient in electrofusion joints. This paper investigates the development of barreling in solid and skinned PE pipes in terms of these frozen in stresses. Residual stresses are predicted using a thermoelastic model and compared with experimental data obtained using the layer removal method. A shell-theory solution for barreling is coupled to the numerical analysis to determine the deflection of the pipe wall near the cut end. Barreling is simulated for PE pipe of various dimensions and processing conditions. The model is validated with experimental data and the effect of barreling on electrofusion joints is discussed in terms of common procedures and standards.

1. Introduction

Although the lifetime of polyethylene (PE) pipes has been demonstrated to far exceed the typical 50 year design life [1], it may be limited by the performance of the fusion joints [2]. Despite all the advantages and better performance of PE pipes over other pipe systems, failures in the field have been reported [3], and these usually involve the joints between the pipes rather than the pipe itself. Joint failures are found to occur in both electrofusion (EF) joints and mechanical fittings. Becetel [4] reported that the failure percentage of laboratory tested EF joints in 2005 was 26.6%, with irregular and excessive scraping as the main cause of failure.

The quality of EF joints depends on several design factors and processing conditions. In addition to fusion time and temperature, the pressure acting on the melt during fusion is important. Whereas in butt welding the pressure is usually applied through axial compression, in EF joining it builds up as the internal surface of the coupler, and the external surface of the pipe in contact with it, melt and expand. Regions near each end of the coupler, and halfway along it where the pipe ends meet, remain unheated: these *cold zones* maintain the pressure by restricting axial extrusion of molten polymer from the fusion zones [5]. Therefore, excessive gaps between the coupler and the pipe may result in insufficient build up of the melt pressure and lower interface temperatures as the melt flows outside the cold zones [5,6] reducing the joint strength.

When a pipe is cut to length, residual stresses set-up during post-extrusion cooling are released through a bending moment, which causes the cut ends to taper inwards, decreasing the diameter of the pipe. Moving back inwards from the cut end, the diameter does not simply increase to its initial value but locally overshoots to a new maximum [7,8]. These variations in diameter near the cut ends are known as pipe 'barreling' and can be inconvenient in EF joints as they generate gaps between the EF coupler and the pipe. Although barreling cannot practically be completely avoided, its effect can be compensated for when designing the couplers or the joining process. This paper

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doi:10.1016/j.polymertesting.2012.02.009

investigates the development of barreling in terms of residual stresses set up during post-extrusion cooling of solid (monolayered) and skinned (bilayered) pipes.

2. Modeling

2.1. Thermal analysis

2.1.1. Monolayered pipes

A pipe at uniform initial temperature T_0 is cooled down in a uniform environment at T_R. The pipe loses heat from both surfaces, which have surface heat transfer coefficients of h_{ext} and h_{int}, which vary as the pipe moves into different cooling units and annealing zones. The temperature distribution across the thickness of the pipe is calculated by means of a one-dimensional heat transfer analysis. The general heat conduction equation in cylindrical coordinates is expressed as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \rho H_c\frac{\partial X_c}{\partial t} = \rho c\frac{\partial T}{\partial t} \qquad (1)$$

where k is the temperature dependent thermal conductivity, ρ the density of the material, H_c the total latent heat of fusion, X_c the fraction of crystallised material and c the specific heat.

To estimate the mass fraction of polymer that has already crystallised, ΔX_c, a kinetic model proposed by Phillips and Manson [9] for predicting absolute crystallinity is coupled to the thermal analysis. The model is based on the Tobin modification of the Avrami equation [10], which considers growth site impingement, and on the Choe and Lee [11] incorporation of homogeneous and heterogeneous nucleation terms.

To apply the control volume method, a pipe of thickness h is divided into layers of thickness Δr, with the surface layers having a thickness $\Delta r/2$, so that the node spacing is uniform (Fig. 1). Temperatures at the nodes are calculated at time intervals Δt. Many textbooks explain the basis of this method [12], in which the temperature at node i after an elapsed time of $m\Delta t$ is used to calculate its temperature at time $(m+1)\Delta t$.

2.1.2. Bilayered pipes

The heat transfer analysis presented previously was extended to bilayered pipes. A PP skin of thickness t is added to the core PE pipe of thickness h (Fig. 1). As an additional boundary condition it is considered that the interface does not store energy.

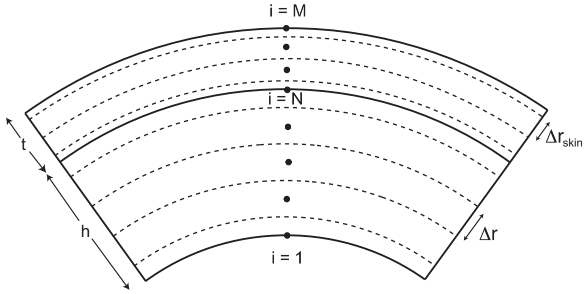

Fig. 1. Division of a pipe of thickness h and skin thickness t for explicit finite difference heat transfer calculations.

2.2. Residual stresses

Residual stresses may arise from various origins: pressure-induced stresses, shear or flow-induced stresses and thermal stresses. Pressure-induced stresses are developed due to packing pressure. Flow-induced stresses are developed during the non-isothermal flow of the polymer melt into a mould or through an annular die, due to the incomplete relaxation of the polymer chains before the polymer freezes. They are an order of magnitude lower than the residual thermal stresses [13] and will be neglected. Thermal stresses appear during cooling. In extrusion, for example, the outer wall of a pipe is cooled faster than the inner one and, as the material cools down, frozen-in strains are developed in the solid phase due to the constraint in the thermal volume contraction induced by crystallisation. These give rise to stresses through the modulus of the solid material. To calculate the residual stresses in the pipe, the temperature gradients at the moment of solidification are integrated to form the residual temperature field, T_{res}. The residual stress distribution, $\sigma_{res}(r)$, is calculated with the following equation [14]

$$\sigma_{res}(r) = \frac{E_\infty}{1-\upsilon}\alpha\left[\overline{T}_{res} - T_{res}(r)\right] \qquad (2)$$

where $\overline{T}_{res}$ is the average value of T_{res} through the specimen thickness, α is the coefficient of thermal expansion, υ is the Poisson's ratio and E_∞ the long term modulus of the material, considering that after a long time at room temperature the relaxation modulus $E(t')$ becomes equal to E_∞ (240 MPa).

2.3. Barreling

When the length of a pipe is cut, the bending moment developed due to the presence of residual stresses reduces the diameter of the pipe at the cut end, giving the pipe a 'barrel' shape. Shell theory is here used to calculate the variations in diameter along the pipe. This is the case of a cylindrical shell bent by moments, M_z, induced by cutting of the pipe and distributed around the cut edges, Fig. 2. For the case of melt-extruded isotropic pipes it is reasonable to assume that the thermal stresses induced during crystallisation are equal in the axial and hoop directions, and thus M_z can be obtained by integrating the residual stresses Eq. (2) throughout the thickness of the pipe.

The solution of this problem was presented by Timoshenko and Woinowsky-Krieger [15] for the case of

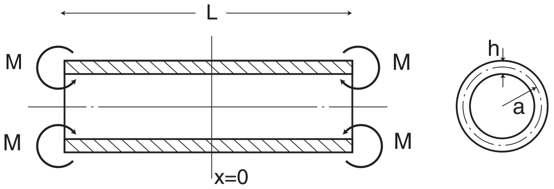

Fig. 2. Cylindrical shell bent by moments.