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

Andrea Guevara-Morales and Patrick Leever
Mechanical Engineering Department, Imperial College London
London SW7 2AZ, UK

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.

Keywords: PE pipes; electrofusion; barreling; residual stresses

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 half-way 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 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

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

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

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 $(m + 1)\Delta t$.

[Figure 1 about here]

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.

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, $\sigma_{\text{res}}(r)$, is calculated with the following equation [14]

$$\sigma_{\text{res}}(r) = \frac{E_{\infty}}{1 - \nu} \alpha [\bar{T}_{\text{res}} - T_{\text{res}}(r)] \quad (2)$$

where $\bar{T}_{\text{res}}$ is the average value of T_{res} through the specimen thickness, α is the coefficient of thermal expansion, ν 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.

[Figure 2 about here]

The solution of this problem was presented by Timoshenko [15] for the case of long shells. However, the solution was here extended for short shells, as the pipes available for measurement had different lengths. For short shells the bending at one end cannot be considered as independent of the conditions at the other end, and the general solution becomes

$$\omega = C_1 \sin \beta x \sinh \beta x + C_2 \sin \beta x \cosh \beta x + C_3 \cos \beta x \sinh \beta x + C_4 \cos \beta x \cosh \beta x \quad (3)$$

where ω is the deflection of the shell in the radial direction and β is a function of the elastic modulus and geometry of the pipe. If the origin of coordinates is taken at the middle of the cylinder, Eq. 3 must be an even function of x , hence $C_2 = C_3 = 0$. C_1 and C_4 are found with the boundary conditions for this particular problem

$$M_z = -D \left(\frac{d^2 \omega}{dx^2} \right)_{x=\frac{L}{2}} \quad (4)$$

$$Q_z = -D \left(\frac{d^3 \omega}{dx^3} \right)_{x=\frac{L}{2}} = 0 \quad (5)$$

where D is the flexural rigidity of the shell and Q_z the shear or tangential forces applied at the boundary.

3. Results

The numerical values of the parameters used in the simulation were either determined experimentally or found in literature. They are listed in Table 1.

Processing Conditions				
T_0	Initial Temperature [°C]	160		
T_R	Room Temperature [°C]	20		
h_{ext}	External Heat Transfer Coefficient [W/m²K]	1250-2000		[16]
h_{int}	Internal Heat Transfer Coefficient [W/m²K]	6		[17]
Pipe Geometry				
$\emptyset$	Diameter [mm]	110-250		
SDR	Standard Dimension Ratio	11		
t	Skin Thickness [mm]	0.4-1.5		
Material Properties		PE	PP	
ρ	Density [kg/m³]	940	900	Pycn.
c	Specific Heat [J/kgK]	2000	1900	[18]
$k(T)$	Thermal Conductivity [W/mK]	0.206-0.355	0.131-0.241	[19]
H_c	Latent Heat of Fusion [kJ/kg]	289	209	[9,20]
T_m	Melting Temperature [°C]	130	130	DSC
T_m^0	Equilibrium Melting Temperature [°C]	140	185	[9,18]
T_g	Glass Transition Temperature [°C]	-125	-10	[9,18]
$X_{c\infty,hom}$	Homogeneous Equilibrium Crystallinity	0.59	0.43	DSC
$X_{c\infty,heter}$	Heterogeneous Equilibrium Crystallinity	0.74	0.52	DSC

Table 1: Material properties and cooling conditions used in the simulations

Monolayered pipes

Figure 3 shows the predicted residual stress profiles for pipes of different diameters. It is observed that pipe size in this range does not seem to significantly affect the residual stress distribution, as found previously by Argyrakis [21]. Also, as expected

for single cooled pipes, residual stresses are tensile at the inner surface and compressive at the outer surface. Tensile stresses at the inner surface are approximately 3 MPa, in agreement with results of Guan et al. [22]. Compressive stresses at the outer surface vary from 15 MPa for 110/11 pipes to 18 MPa for 250/11 pipes, and are significantly higher than measured values reported in the literature (~4 MPa) [23,24]. Pittman and Farah [25] developed a viscoelastic method to predict residual stresses using temperature dependent properties, but, Guan et al. suggested that those predictions seem to be underestimated.

[Figure 3 about here]

To obtain more accurate results, the layer removal method was used to determine the residual stress distribution through the thickness of the pipe using axially-cut pipe strips. After axial strips were cut from the pipe they developed creep curvature at a progressively decreasing rate over 5-7 days. The approach to a steady state was monitored by periodically measuring the central deflection of an arc of constant length using a coordinate measuring device. For convenience, since the removal of layers by milling took time and required some strips to be held straight by clamping, the creep process in full-thickness strips was frozen by storage at low temperature in a conditioning unit at -20°C. To avoid bending the specimens during the curvature measurements, they were embedded in a commercial cold mounting acrylic resin filled with aluminium silicate. This resin cures at room temperature with virtually zero shrinkage, which guarantees that no additional deformation is imposed to the specimens. Residual stresses were determined using the relationship established by Treuting and Read [26] for equibiaxial stresses

$$\begin{aligned} \sigma_x(z_1) &= -\frac{E}{6(1-\nu^2)} \left\{ (z_0 + z_1)^2 \left[\frac{d\varphi_x(z_1)}{dz_1} + \nu \frac{d\varphi_y(z_1)}{dz_1} \right] + 4(z_0 + z_1)[\varphi_x(z_1) + \nu\varphi_y(z_1)] \right. \\ &\quad \left. - 2 \int_{z_1}^{z_0} [\varphi_x(z) + \nu\varphi_y(z)] dz \right\} \end{aligned} \quad (6)$$

where $\sigma_x(z_1)$ is the stress in the longitudinal direction of the specimen at a distance z_1 from the original mid-surface of the specimen, z_0 is half the thickness of the original specimen and $\rho(z)$ is the curvature. The term $-2z_0\rho_0$ accounts for the initial curvature of the specimen which should be subtracted from subsequent values. Figure 4 shows a layer of thickness $z_0 - z_1$ to be removed from an axially-cut pipe strip. Curvatures were measured on the inner surfaces as they have the best surface finish.

[Figure 4 about here]

It is observed that the experimental results from layer removal on axial strips are very similar to those predicted by the simulation. Much higher residual stresses at the outer surface of the pipe were found than those obtained from ring slitting [27,28]. Although these values are much higher than those reported elsewhere (using ring slitting techniques), it was found that Mills [22] applied a similar experimental technique based on scanning the surface of small samples cut from a pipe wall to accurately

measure deformations, and his results for MDPE pipes were 50% higher than others. They found axial and hoop stresses of ~ 6 MPa at the outer surface of the pipes. HDPE pipes have higher elastic modulus, and hence higher residual stresses are expected.

The deflection of the pipe wall in the radial direction was predicted with Eq. 3. Results are shown in Fig. 5. The cut ends are used as reference points so the deflections are measured from them. Experimental data was obtained by measuring the change in diameter using a dial indicator (accuracy ± 0.01 mm). The external heat transfer coefficients reported by Pittman et al. [16] for pipes of different dimensions were used for the simulations: $1250 \text{ W/m}^2\text{K}$ (110/11, 125/11), $1750 \text{ W/m}^2\text{K}$ (180/11) and $2000 \text{ W/m}^2\text{K}$ (250/11). Good agreement between the experimental and predicted results is observed for all the pipes. As mentioned before, these variations in diameter near the cut-ends can be inconvenient in EF joints as it generates gaps between the EF coupler and the pipe. From Fig. 5, if the gap between the cut-end and the zone where the pipe reaches its maximum diameter is measured, it is found to be approximately 1-1.2% of the pipe nominal diameter.

[Figure 5 about here]

Bilayered pipes

Figure 6 shows the measured and experimental residual stress profiles for pipes with different skin thickness. It is observed that the thicker the skin, the lower the residual stresses. For a 1.5 mm skin residual stresses at the outer surface were reduced by a third, from ~ 15 MPa to ~ 5 MPa. The degree to which residual stresses at the inner surface were reduced was similar, from ~ 3 MPa to ~ 2 MPa for 1.5 mm skin. Although the heat transfer coefficient at the inner surface remained unchanged, conduction through the polymer was reduced and, therefore, sections near to the inner surface remained at higher temperatures for longer periods. Very good agreement was found between the analytical and experimental results.

[Figure 6 about here]

The deflection of the pipe wall in the radial direction was predicted with Eqs. 3-5. Results are shown in Fig. 7. Again, good agreement is found between experimental and predicted results. Although the deflection profile is similar for the monolayered and bilayered pipes, the radial gap is reduced with increasing skin thickness as residual stresses decrease.

[Figure 7 about here]

4. Discussion

In EF fittings, heating wires are moulded-in or implanted into the fusion zone, acting as the heat source. As shown in Fig. 8, cold zones are located at both sides of the fusion zone to block off the extrusion of any molten polymer from the fusion zone [5]. Therefore, excessive gaps between the coupler and the pipe may result in insufficient build up of melt pressure and lower interface temperatures as the melt flows outside the cold zones, reducing the joint strength [5,6]. The dimensions of the

cold and fusion zones for each pipe according to the UK WIS-4-32-14 standard [29] are also shown in Fig. 5 and 7. It is observed that most of the gap is located at the inner cold zone, which may allow the polymer melt to flow, reducing the build up pressure, and thus reducing the strength of the joint.

[Figure 8 about here]

In Fig. 9, the maximum allowable gap according to the GIS/PL2 2-4 standard [30] and including scraping (material removal to expose a clean virgin surface for EF) is shown and compared with the gap introduced by barreling. It is observed that for diameters larger than 150mm, the gap introduced by barreling is higher than the maximum allowable gap, and that the effect is more significant for larger diameters. Although barreling can be minimised by optimising cooling conditions it cannot be completely avoided and its effect should be considered when designing the joining process (ie. scraping of the pipe and coupler design).

[Figure 9 about here]

In the case of skinned pipes, the PP skin protects the PE pipe by absorbing installation damage. When it is removed it reveals an undamaged pipe surface suitable for EF joining, which optimises and reduces installation times. A less advertised advantage is that the lower residual stresses in the core PE pipe produce a lower bending moment when the pipe is cut, reducing barreling and thus further improving the quality of the joint. This effect can be observed in Fig. 10, where the variations in diameter near the cut ends for peeled 110/11 pipes are shown. It is observed that the thicker the PP skin was, the less the barreling at the cut ends, as predicted in Fig. 7.

[Figure 10 about here]

The maximum allowable gap for 110 mm pipe is 1.18% (Fig. 9). As mentioned previously, for small pipes (diameter<150 mm) the gap introduced by barreling is smaller than that allowable. However, if the pipe is scraped the diameter is reduced by ~ 0.3 mm, which in addition to the gap introduced by barreling might be above the allowable value. In the case of skinned pipes not only is the need for scraping avoided, but also the barreling gap is reduced even further. For 1.5 mm skinned pipes, it is reduced by approximately 40%, to well below the maximum allowable gap limit.

5. Conclusions

When a pipe is cut to length residual stresses set up during cooling are released through a bending moment causing the cut ends to curl inwards, reducing the diameter of the pipe and giving the cut end a barreled shape. Residual stresses were integrated to obtain the bending moments acting at the edge of the pipes and shell theory was then used to estimate the deflection of the pipe wall in the radial direction. The higher the residual stresses in the pipe, the more the deflection at the cut ends.

These variations in diameter can generate gaps between the pipe and an electrofusion coupler, which can reduce the quality of the joint by allowing polymer melt to flow out the fusion zones reducing the built-up pressure. The gaps introduced by barreling were compared to the maximum allowable gap for EF joining according to the

standards, it was found that for diameters larger than 150 mm, the gap introduced by barreling is wider than that allowable, and that the difference between them is more significant for larger pipes as the allowable gap decreases with increasing diameter.

In the case of skinned pipes, the skin not only protects the pipe during installation or reveals an undamaged pipe surface for EF joining when it is removed, but it also reduces barreling as the levels of residual stresses within the pipe are lower. Therefore, the gap between the EF coupler and the pipe is not only minimised by the 'non-scraping' process, but also by the reduction of barreling near the cut ends, which will probably lead to stronger EF joints.

6. Acknowledgments

A. Guevara gratefully acknowledges the financial support from the Mexican National Council for Science and Technology (CONACyT) and Radius Systems Ltd.

References

- [1] M. Rozental-Evesque, D. Geoffray, P. Jacq, and B. Rabaud. In: *Plastics Pipes XV*, Vancouver, BC Canada, 2010.
- [2] D. Lowe, P. Starkey, and E. Ingham. In: *Plastics Pipes XIV*, Budapest, Hungary, 2008.
- [3] S. MacKellar. In: *Plastic Pipes XIII*, Washington, USA, 2006.
- [4] P. Vanspeybroeck. In: *Plastics Pipes XIII*, Washington, DC, 2006.
- [5] J. Bowman. A review of the electrofusion joining process for polyethylene pipe systems. *Polym Eng Sci* 1997; 37(4):674.
- [6] R. Eckert. In: *Plastics Pipes XIV*, Budapest, Hungary, 2008.
- [7] A. Guevara Morales and P. S. Leever. In: *Plastics Pipes XV*, Vancouver, BC Canada, 2010.
- [8] A. Guevara Morales and P. S. Leever. In: *SPE ANTEC 2011*, Boston, MA USA, 2011.
- [9] R. Phillips and J.E. Manson. Prediction and analysis of nonisothermal crystallization of polymers. *J Polym Sci B: Polymer Physics* 1997; 35(6):875.
- [10] M.C. Tobin. Theory of phase transition kinetics with growth site impingement. I. homogeneous nucleation. *J Polym Sci* 1974; 12:399.
- [11] C.R. Choe and K.H. Lee. Nonisothermal crystallization kinetics of poly(etheretherketone) (PEEK). *Polym Eng Sci* 1989; 29(12):801.
- [12] F. Kreith and M.S. Bohn. *Principles of heat transfer*. 6th ed. Brooks Cole Thomson Learning. 2001.
- [13] Wen-Bin Young. Residual stress induced by solidification of thermoviscoelastic melts in the postfilling stage. *J Mater Process Tech* 2004; 145(3):317.
- [14] V. Tropsa. Predicting residual stresses due to solidification in cast plastic plates. PhD thesis, Imperial College of Science, Technology and Medicine, 2001.
- [15] S.P. Timoshenko and S. Woinowsky-Krieger. *Theory of plates and shells*. 2nd ed. McGraw-Hill. 1959.
- [16] J.F.T. Pittman, I.A. Farah, A. Eccott, and D.H. Isaac. In: *Plastics Pipes IX*, Scotland, UK, 1995, p. 529–533.
- [17] P. S. Leever, S. Hillmanssen, and L. de F. Moreno. Specimen temperature conditioning and drift before an S4 pipe fracture test. *Polym Test* 2004; 23(6):727.
- [18] J. Brandrup. *Polymer Handbook*. 4th ed. Wiley. 1999.

- [19] X. Zhang, W. Hendro, M. Fujii, T. Tomimura, and N. Imaishi. Measurements of the thermal conductivity and thermal diffusivity of polymer melts with the short-hot-wire method. *Int J Thermophys* 2002; 23(4):1077.
- [20] J.E. Mark. *Physical Properties of Polymers Handbook*. AIP Series in Polymers and Complex Materials. AIP Press. 1996.
- [21] C. Argyrakis. Models for designing pipe-grade polyethylenes to resist rapid crack propagation. PhD thesis, Imperial College London, 2010.
- [22] Z.W. Guan and J.C. Boot. A method to predict triaxial residual stresses in plastic pipes. *Pol Eng Sci* 2004; 44(10):1828.
- [23] J.G. Williams, J.M. Hodgkinson, and A. Gray. The determination of residual stresses in plastic pipe and their role in fracture. *Polym Eng Sci* 1981; 21(13):822.
- [24] A. Kazakov. An automated method for the measurement of residual stress in melt-extruded plastic pipes. *Polym Test* 1998; 17(6):443.
- [25] J.F.T. Pittman and I.A. Farah. Comprehensive simulation of cooling process in plastic pipe manufacture. *Plast Rub Compos Pro* 1996; 25(6):305.
- [26] R.G. Treuting and W.T. Read, Jr. A mechanical determination of biaxial residual stress in sheet materials. *J Appl Phys* 1951; 22(2):130.
- [27] A. Bhatnager and L.J. Broutman. In: *Ninth Plastic Fuel Gas Pipe Symposium*, New Orleans, 1985.
- [28] P. Yayla. Rapid crack propagation in polyethylene gas pipes. PhD thesis, Imperial College of Science, Technology and Medicine, 1991.
- [29] UK Water Industry. Specification for PE80 and PE100 electrofusion fittings for nominal sizes up to and including 630, 1995.
- [30] National Grid. Gas Industry Standard: Specification for polyethylene pipes and fittings for natural gas and suitable manufactured gas, 2008.

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

Figure 2: Cylindrical shell bent by moments

Figure 3: Predicted and experimental residual stress distributions for PE pipes of different size. a) 110/11, b) 125/11, c) 180/11 and d) 250/11.

Figure 4: Layer to be removed from an axially-cut pipe strip

Figure 5: Barreling in solid PE pipes - deflection of the pipe wall in the radial direction

Figure 6: Predicted and experimental residual stress distributions for 110/11 PE/PP pipes with different skin thickness. a) No skin, b) 0.4 mm skin, c) 0.8 mm skin and d) 1.5 mm skin.

Figure 7: Barreling in peeled 110/11 PE pipes - deflection of the pipe wall in the radial direction

Figure 8: Gap between EF coupler and pipe due to barreling

Figure 9: Maximum allowable gap between EF coupler and pipe compared to gap produced by barreling

Figure 10: Barreling at cut ends of peeled 110/11 skinned pipes. a) No skin, b) 0.4 mm skin, c) 0.8 mm skin and d) 1.5 mm skin.

(a)

(b)

(c)

(d)