STUDY OF L/D RATIO EFFECT ON RESIDUAL HOOP STRESS EVOLUTION IN POLYETHYLENE PIPE

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Abstract

In extrusion process of polyethylene tubes, it is known that residual stresses are the consequences of manufacturing process, which requires homogeneous geometric dimensions of diameter and thickness. These impose rapid cooling from the outer tube surface. Ring specimens' were cut along a generatrix from a High Density Polyethylene (HDPE) tube to evaluate the residual stress evolution. Technique used in experiments as presented in a later study, involves on assessing residual deformation as function of ratio (L/D) over a period of time. Then, after determining the creep modulus, residual stress was measured for each ratio (L/D). Deformation values increase towards a plateau after 120h, showing a trend approaching a constant over time. This result is corroborated further by L/D=2, the greater is the diameter, the more this pattern is supported. We can presume that the deformations progress towards a condition of plane deformation. Strain-time curves show typical creep behavior of semi-crystalline viscoelastic materials such as HDPE. Results indicate that the calculated residual hoop stress is negative. In plastic pipe manufacturing, low quench water temperature results in high compressive residual stress at the outer pipe surface.

Keywords: *HDPE, Extrusion, Ratio (L/D), Creep modulus, Residual hoop stress.*

I. Introduction

High Density Polyethylene (HDPE) ranks third in the world by volume among commodity plastics, after polyvinyl chloride and polypropylene. The HDPE market is expanding, with production and demand expected to increase sharply between 2022 and 2027. Asia continues to be the preferred place for demand. The recent expansion of the polyethylene sector has pushed manufacturing centers to relocate to regions with access to raw materials, such as the Middle East, or to regions with strong domestic demand, such as mainland China [1]. Numerous sectors have seen a surge in the utilization of polymer materials. Applications utilizing pressure pipes, such the distribution of natural gas, the purification of drinking water, and the disposal of wastewater, are recognized as examples of large-scale technological advancement. In fact, because of their appealing mechanical qualities, affordable production costs, and simplicity of processing, customers have chosen this class of materials. Polymer constructions need to be sized and manufactured correctly in order to endure the numerous mechanical and/or environmental loads to which they are subjected during their service [2]. We may mention two industrial thermoplastic shaping processes: injection and extrusion molding, the latter of which is primarily utilized in the manufacturing of long items like polyethylene connectors. The idea is to use an extruder to melt and plasticize polymer grains, then an extrusion head to shape the material [3]. It is acknowledged that residual stresses and morphological variations in extruded tubes result from the manufacturing process, which necessitates homogeneous geometric dimensions in terms of thickness and diameter, which calls for quick cooling. As a result, during the extrusion process, the tube's outer layers experience compressive stresses while its inner layers experience positive stresses. These residual stresses play a major role in determining the resistance to crack propagation. Additionally, it has been demonstrated that in outer layers that are subject to compressive residual stresses, the propagation of cracks is slower [4,5]. It is well known that residual stresses from manufacturing processes are present in all polymer tubes. Depending on the manufacturing processes used, residual stresses can vary greatly in size and distribution. In the course of cooling, differential shrinkage across the tube wall is one of the primary causes of residual stress [6]. The residual stresses in polyethylene pipes are calculated in this study using an experimental methodology. In fact, L/D ratio where L and D are ferrules length and diameter and the change in creep modulus are used to measure these stresses.

II. Material and methods

Material

In this study, high-density polyethylene (HDPE-100) material was employed, it was manufactured by the Algerian plastic pipe company TUBOGAZ of ANNABA in its tubular form, they have a standard dimension ratio of 17 and two diameters of 90 mm and 110 mm, and they are designed for the distribution of drinking water [7].

Table 1. Technical Specifications of HDPE-100 [7]

Properties	Values	Standards
Density [kg/m³]	956- 961	ISO 1183
Melt Flow Index MFI [g/10min]	0.2- 0.5	ISO 1133
Young's Modulus[N/mm²]	~ 1200	DIN 53457
Failure Stress [N/mm²]	~ 24	ISO 6259
Failure Strain [%]	>500	ISO 6259
Hardness Shore at 20°C [-]	59	ISO 868
Resilience at 23°C [J/m²]	>600	ASTM D256
Ultimate Elongation (%)	≥350	-
Yield Elongation at 23°C (%)	9	-

Ring slitting method

The method for preparing test specimens involves slitting or cutting the tube on a universal turning machine altering the longitudinal progress. A wooden mandrel is created to retain the tube during machining. High speed steel with a thickness of 5 mm is the cutting material. A speed of 45 rpm is chosen to reduce the impact of the generated heat during cutting at 25°C (Fig 1).

The chosen specimens are shaped like rings of various widths, as seen in Fig 1 (c). Using a cutter blade attached in the tool holder and a slow rotating speed, the two pipes are formed into rings. The widths of the specimens, which were machined from two 110 and 90 mm tubes, are a function of the diameter. L/D = (0.1, 1, and 2) is one of the eight L/D ratios examine [8].

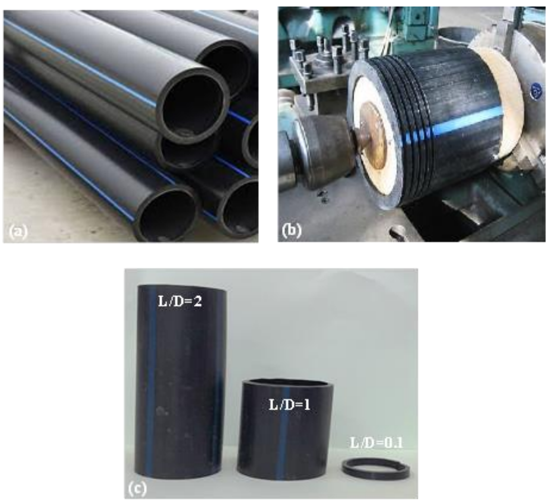

Figure1. Ring slitting method, (a): HDPE Pipe, (b): Pipe cutting operation, (c): Specimens in rings shape.

Residual displacement

The behavior-deformation as a function of diameter D and ratio L/D in time is the center of the observations made during the experiment.

Three ratio cuts from the 90 mm and 110 mm diameter tubes are used to represent the deformations as a function of time. As expected, it is seen that the deformation rises with t and approaches a nearly constant plateau at t around 7 days.

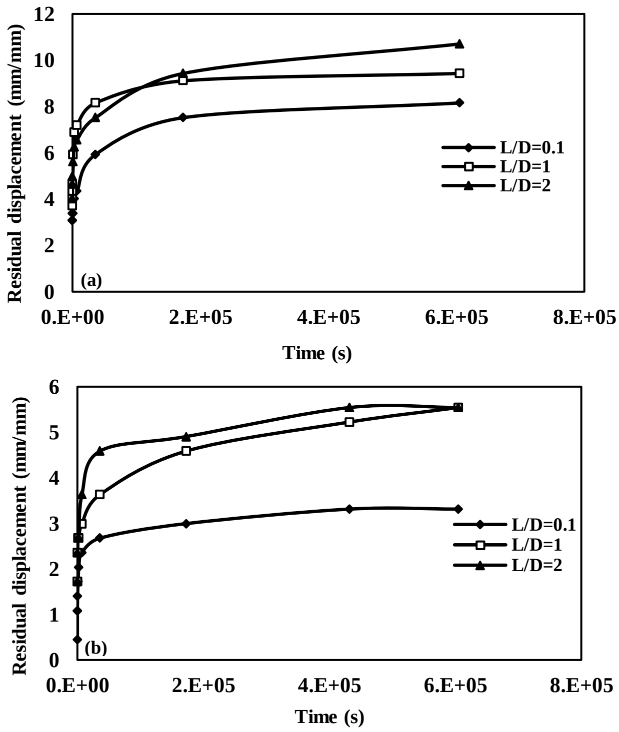

Figure2. Residual displacement vs. time curves for diameters: (a) D 90mm, (b) D110 mm.

III. Calculation approach

Residual stress measurements

The residual stress is based on the deflection that shows the change in the periphery of the ring which decreases or increases over time. By measuring the ring diameter at a specific time, the maximum residual hoop stress can be calculated by the relation (1) developed by Broutman et al., [9].

$$\sigma(Max) = \pm \frac{E(t)h_0}{1-\nu^2}\left(\frac{D_1(t) - D_0}{D_1(t).D_\circ}\right) \qquad (1)$$

Where:

$\sigma_{(Max)}$: Maximum residual hoop stress, (MPa)

E (t): Creep Modulus at time t, (MPa),

h_0: Pipe thickness, (mm),

D_0: Mean diameter before slitting, (mm),

D_1 (t): Mean diameter after slitting at time t, (mm),

t: Time, (hours),

ν: Poisson ratio.

Creep modulus

The Creep modulus can be calculated using the relation (2) developed by Broutman et al., [9], with the constants

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a = -49.32 and b =509.99 taken from curve shown in (Fig3).

$$E(t) = a\ln(t) + b \quad (2)$$

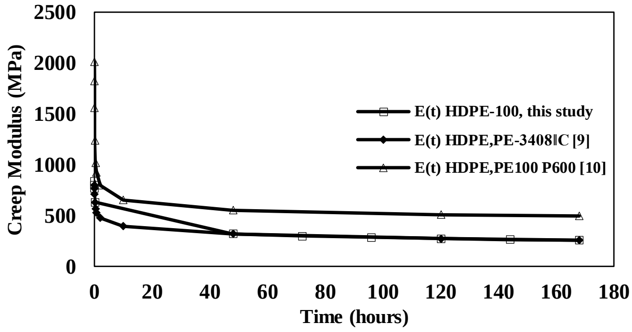

Figure3. Creep modulus E (t) vs. time for HDPE in comparison with literature.

Plastics display distinct viscoelastic behavior, i.e. the reaction to a mechanical load depends not lone on temperature but similarly on time. The time-delayed deformation owing to a constant external load is devoted to as creep. The creep modulus curve was an upper limit curve agreeing to 0 applied stresses resulting from the creep modulus curves found in the literature because creep modulus increases with decreasing applied stress and there is no applied stress during the residual stress measurements [10]. Figure 3 shows a summary of available creep modulus values of thermoplastic materials, especially HDPE [9,10].

Creep is the physical phenomenon which causes the delayed irreversible deformation, i.e. not instantaneous, of a material subjected to a constant stress (thermal or mechanical), even lower than the elastic limit of the material. For a period of time, creep modulus is high enough in the short term, and it is reduced in the long term. The creep behavior can be separated in primary creep with regressive behavior where the creep rate decreases and a secondary creep where the creep rate is almost constant (Fig.3).

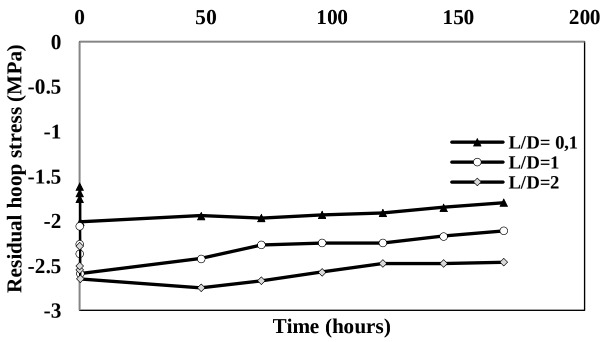

Figure4. Residual hoop stress vs time, D 90mm.

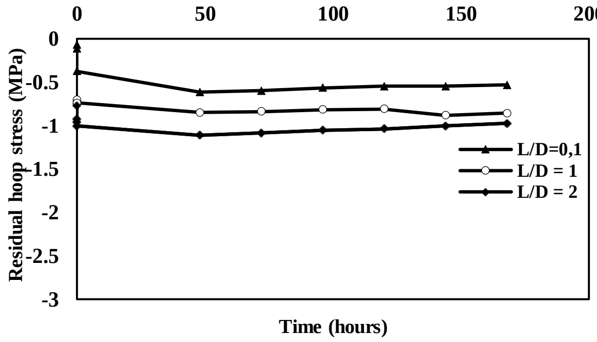

Figure5. Residual hoop stress vs time, D 110 mm.

Fig. 4 and Fig. 5 describes variations of the maximum residual hoop stress on the outer surface vs. time after the ring-slitting, which are resultant of substituting the variations of creep modulus in Fig. 3 into the Eq. (1). From the calculated values, it can be found that residual hoop stresses close to outer surface are compressive. These compressive residual stresses are common phenomenon of the HDPE pipes manufactured by extrusion process [4]. As depicted in Fig.4 and Fig. 5, after the ring-slitting, total values of the maximum residual hoop stresses instantly increase and then slowly increase. After more than 120hours (5 days) the maximum residual hoop stresses are almost constant.

For the tube with a diameter equal to 90 mm, and in the three ratios studied, we found that the value of the residual stress varies from -1.61MPa to -1.79MPa when L/D=0.1, from -2.05MPa to -2.11MPa when L/D=1, and finally from -2.28MPa to -2.46MPa at L/D=2 (Fig. 4).

In the second case studied, where the diameter is equal to 110mm, and in the three ratios we found that the value of the residual stress varies for example in the case where L/D=0.1 from -0.06MPa to 0.53MPa, when L/D=1 it varies from -0.71MPa to -0.85MPa, and for L/D=2, it varies from -0.77MPa to -0.97MPa (Fig. 4).

IV. Conclusions

In this work, experimental approach was used to evaluate residual stresses in polyethylene pipes at two distinct diameters (i.e., 90mm and 110mm), and for three different ratios (L/D) = (0.1, 1, 2). The experimental procedure consists of measuring the deformation over time in relation to the width (length) and diameter of the test piece:

1. Extruded HDPE pipes exhibit compressive negative residual stress.

2. For tube with D=90 mm, in the three ratios studied, values of residual stress varies from -(1.61 to 1.79)MPa for L/D=0.1, from -(2.05 to 2.11)MPa for L/D=1, and from -(2.28 to 2.46)MPa at L/D=2.

3. For D= 110mm, residual stress varies for L/D=0.1 from -(0.06MPa to 0.53)MPa, when L/D=1 it varies from -(0.71 to 0.85)MPa, and for L/D=2, it varies from -(0.77MPa to 0.97)MPa.

4. After ring-slitting, global values of residual hoop stress instantly increase and then slowly increase. Later more than 120 hours residual hoop stress values are almost constant.

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