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Test Method

The viscoelastic effect during acoustoelastic testing of polyethylene

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ABSTRACT

The aim of this work is to investigate the viscoelastic effect during acoustoelastic testing of a thermoplastic (polyethylene) for a reliable stress evaluation, which is critical for the processing and in-service life of thermoplastic products. The strain accumulated under step loading-holding stages was firstly characterized by a stepped isostress method, which can be integrated into the acoustoelastic equations. A nonlinear acoustoelastic term was also introduced in order to explain the viscoelastic effect from the increasing stress/strain. Although different holding times and loading rates will change the ultrasonic wave velocity profiles, their influences can be correlated and included in the improved acoustoelastic equations. Furthermore, the nonlinear problem can be circumvented by using an acoustic birefringence technique. Finally, the traditional and nonlinear acoustoelastic coefficients of polyethylene were calculated and verified.

1. Introduction

Thermoplastics are becoming increasing important in modern industry as a growing alternative to metals because of their high impact resistance, weldability and recyclability. This type of material is sensitive to processing conditions which will influence the porosity, crystallinity, residual stresses, anisotropy, etc … [1]. Each factor is sometimes coupled with others and together further determine the final mechanical properties. Due to this complexity, additive manufactured thermoplastic products still have inferior and unstable mechanical behavior compared to traditional extrusion or injection molded parts [2]. This situation becomes more intricate when fibers are incorporated for composite parts [3]. Hence, understanding the influences of different factors becomes the key for wider applications of thermoplastics.

Among all these factors, residual stresses (in self-equilibrium state in samples) are difficult to evaluate directly. The residual stress magnitude is normally found to be in the range of 1–10 MPa in thermoplastics such as injection molded polycarbonate samples [4,5] and as high as 50 MPa in fiber reinforced thermoplastic composites such as consolidated carbon/PPS laminates [6]. Various techniques have been developed for residual stress evaluation including destructive (e.g. layer remove method [7], compliance method [8]) and non-destructive methods (e.g. tomography [9], optical fiber [10]), most of which are modified from methods for metallic materials with lattice structure. Only a few of these evaluation methods are suitable for thermoplastics with the entanglement chain structure and semi-crystalline state.

Acoustoelasticity has been shown to be a potential property of thermoplastics in order to evaluate stresses by nondestructive testing. Hughes and Kelly [11] were one of the first to explore the relationship between hydrostatic pressure and dynamic modulus for polystyrene by using acoustoelastic theory. Kruger et al. [12] used brillouin spectroscopy to measure the second order and third order elastic coefficients of polycarbonate under tensile testing. Other contributions focused mostly on the direct stress-velocity measurements of different thermoplastics such as polyamide [13] and polyethylene [14] with longitudinal waves and PMMA [15] with surface acoustic waves. Among these results, the velocity does not always vary linearly with stress. Even at low stress level, nonlinearity has been found during the tensile testing of polycarbonate [12] and polyethylene [14]. Such phenomenon prevents a further application of this method in thermoplastic parts.

During residual stress measurement, the residual stresses and residual strains are always treated interchangeably under the assumption of linear elasticity. However, since viscoelasticity is an intrinsic property of thermoplastics, it becomes non-negligible under long times or high temperatures and brings measurement uncertainty. Poduška et al. [16] have measured circumferential stress magnitude and the influence of residual axial stresses using combined slitting and layer removal methods in extruded polypropylene pipes. The diameter of cutting ring changes with time and interferes with residual stress determination. Magnier et al. [4] have found that viscoelastic deformation takes place when the drilling tool pushes and shears the polycarbonate sample. This strain part will superpose on the strain due to residual stress relaxation. Being able to separate tooling induced strain and residual stress induced strain is critical for reliable residual stress evaluation.

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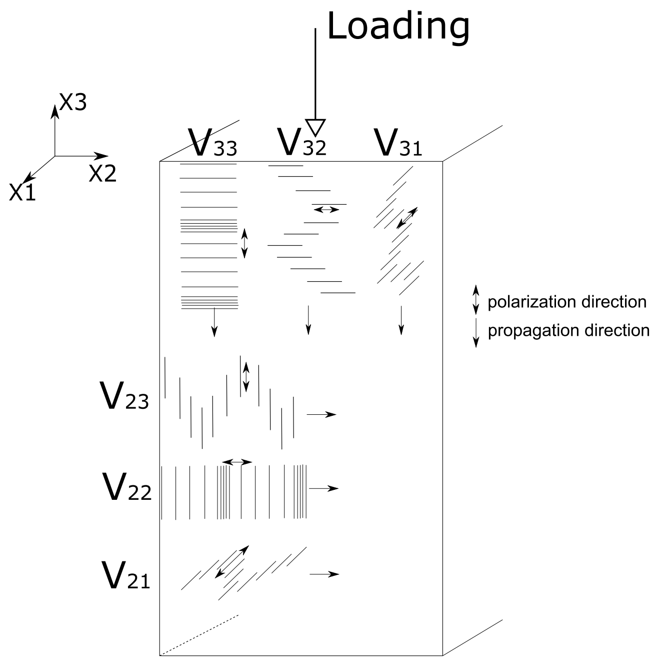

Fig. 1. Wave propagation under uniaxial loading in direction 3.

Here, the viscoelastic effect during the acoustoelastic stress measurement of a thermoplastic material with strong nonlinear viscoelasticity, polyethylene, which is widely used for structural components such as storm pipes and sanitary sewer lines, is investigated. Incorporation of the influence of viscoelasticity into the acoustoelastic testing was attempted, in order to better explain the stress measurement results.

2. Theoretical background

The classical acoustoelastic theory requires that the material behaves as elastic under small strain or stress perturbation. As shown in Fig. 1, when wave propagation direction is along the loading direction 3 [17].

$$\rho^0 V_{33}^2 = \lambda + 2\mu + [4(\lambda+2\mu) + 2(\mu+2m) + \nu\mu(1 + 2l/\lambda)]\varepsilon \tag{1}$$

$$\rho^0 V_{31}^2 = \rho^0 V_{32}^2 = \mu + [4\mu + \nu(n/2) + m(1 - 2\nu)]\varepsilon \tag{2}$$

If wave propagates at direction 2 which is perpendicular to the loading direction 3

$$\rho^0 V_{22}^2 = \lambda + 2\mu + [2l(1 - 2\nu) - 4\nu(m + \lambda + 2\mu)]\varepsilon \tag{3}$$

$$\rho^0 V_{21}^2 = \mu + [(\lambda + m)(1 - 2\nu) - 6\nu\mu - 1/2n]\varepsilon \tag{4}$$

$$\rho^0 V_{23}^2 = \mu + [(\lambda+2\mu+m)(1 - 2\nu) + 1/2n\nu]\varepsilon \tag{5}$$

where V_{ij} means that the wave travels in direction i and polarizes in direction j, ρ^0 is the density in the initial state without deformation, ν is Poisson's ratio, λ and μ are the Lamé coefficients, l, m, n are Murnaghan coefficients, ε and σ represent the axial strain and stress applied along direction 3.

During acoustoelastic testing, the stress or strain-velocity curve can be obtained by step loading-holding stages with incremental loads. The time of flight is recorded at each constant stress holding period, which can be used for velocity calculation. However, when the material is shown to be viscoelastic, the strain accumulates with time and varies at each constant stress holding period. Since ultrasonic measurement is very sensitive to external variations, this brings nonlinearity to the stress-velocity curve measurement.

The testing procedure is analogous to that described in SSM (stepped isostress method). SSM is a recent emerging method for the long-term mechanical behavior prediction such as creep rupture. It has been applied for fibers [18], unidirectional lamina [19], polyamide 6 [20], etc. Similar to SIM (stepped isothermal method) based on TTSP (time-temperature superposition principle) regarding temperature variation, SSM is a stress control method according to TSSP (time-stress superposition principle) [21]. Based on thermodynamic principles, the strain of nonlinear viscoelastic thermoplastics during SSM or stepped loading here can be described by the Schapery's single integral constitutive equation [22]:

$$\varepsilon(t) = g_0 D_0\, \sigma + g_1 \int_0^t \Delta D(\varphi - \varphi') \frac{dg_2\sigma}{d\tau} d\tau \tag{6}$$

if a constant stress is applied, equation (6) changes to

$$\varepsilon(t) = \underbrace{g_0 D_0 \sigma}_{\text{elastic strain}} + \underbrace{g_1 \Delta D\left(\frac{t}{a_\sigma}\right) g_2 \sigma}_{\text{creep strain}} \tag{7}$$

in which

$$\varphi = \int_0^t \frac{dt'}{a_\sigma} \tag{8}$$

$$\varphi' = \int_0^\tau \frac{d\tau'}{a_\sigma} \tag{9}$$

where D_0 and ΔD are the instantaneous and transient viscoelastic creep compliance, g_0, g_1, g_2, a_σ are material parameters that vary with stress, t and τ are time variables. The strain-stress equivalence can be shown as:

$$\varepsilon(\sigma_0, t) = \varepsilon(\sigma, t \cdot a_\sigma) \tag{10}$$

when $g_0 = g_1 = g_2 = a_\sigma = 1$, equation (6) becomes the well-known Boltzmann superposition integral.

For thermoplastics above their glass transition temperature, the Williams-Landel-Ferry (WLF) equation is always used [20] for the time-stress equivalence shift:

$$\log(a_\sigma) = -\frac{C_1(\sigma - \sigma_r)}{C_2 + (\sigma - \sigma_r)} \tag{11}$$

where C_1 and C_2 are constants and σ_r is the reference stress. Below the glass transition temperature, the Eyring equation [18] is more suitable with the shift time-stress expression as:

$$\log(a_\sigma) = \frac{V^*}{2.303kT}(\sigma - \sigma_r) \tag{12}$$

where V^* is the activation volume, k is Boltzmann constant, T is temperature, σ and σ_r are instantaneous stress and reference stress.

3. Experimental

A polyethylene sample (Ertalon, Quadrant) of square cross-section of 49.44 × 49.44 mm^2 and 147.40 mm in length was used. No murnaghan coefficients can be found for this type of thermoplastic in the literature. It was assumed to be isotropic, homogeneous, and without initial stresses. Two holes were made in the sample to centre the sensors during the measurements along the loading direction (Fig. 2).

A commercial ultrasonic generator and recorder with a precision of 10 ns (Krautkramer, General Electric) was chosen to record the time of flight by measuring the first arriving signals with the through transmission technique. The longitudinal sensors (MSW-QC 2.25 MHz, General Electric) and shear wave sensors (K2KY-O 2 MHz, General Electric) were chosen and fixed to the sample with springs to apply constant forces on them during the tests. A traditional honey was chosen as the ultrasound coupling agent. An in-house designed support frame was used to fix and align sensors perpendicular to the loading direction during the measurements.