International Journal of Engineering Science 60 (2012) 37–52

Contents lists available at SciVerse ScienceDirect

International Journal of Engineering Science

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

Modeling of the nonlinear viscoelasticity of polyoxymethylene in tension and compression

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ARTICLE INFO

Article history:
Received 2 March 2012
Received in revised form 3 May 2012
Accepted 29 May 2012
Available online 25 June 2012

Keywords:
Nonlinear viscoelasticity
Polymer
Compression
Tension
Stress relaxation
Creep
Schapery model
Polyoxymethylene

ABSTRACT

An optical measurement technique was used to measure the axial and transverse strain of polyoxymethylene in various uniaxial tensile and compressive loadings. The 3d nonlinear viscoelastic model of Schapery was chosen to describe the time-dependent mechanical behavior. The model equation is solved using a recursive technique, which is used in a nonlinear optimization algorithm to identify model parameters by fitting experimental data. It is shown that the Schapery model is capable of describing the nonlinear viscoelastic relaxation behavior in tension and compression. Furthermore, it is verified that the model determined using stress relaxation data can accurately predict the response to creep and cyclic stress histories. A bending stress relaxation test serves as an exemplary test of a structure with simultaneously occurring compressive and tensile stresses. The model is used in a finite-element simulation of this test to demonstrate its performance in this more complex application.

1. Introduction

Thermoplastics exhibit a strong dependence on the hydrostatic pressure of the elastic properties (Silano, Pae, & Sauer, 1977), time-dependence (Jerabek, Tscharnuter, Major, Ravi-Chandar, & Lang, 2010) and yield behavior (Pae, 1977; Rabinowitz, Ward, & Parry, 1970). Compression testing provides means to characterize the pressure dependence (e.g. Qvale & Ravi-Chandar, 2004), but there are several aspects that complicate compression testing. The ratio of specimen height to diameter has an effect on the testing results: a high ratio leads to buckling, a low ratio implies a stronger influence of friction between the specimen and the compression plates (Khun, xxxx). Thus, a compression specimen machined from a tensile specimen with 4 mm thickness may have a length between 8 mm and 10 mm for a ratio between 2 and 2.5. In this case, a strain of 0.1% corresponds to a length change of only 10 μm. This illustrates the high precision requirements on the load transmission and specimen manufacture imposed by the low specimen length especially for precise measurements in the low strain range. Due to the simplicity of tensile testing, mechanical characterization is often based on tensile testing only. Consequently this is also true for modeling efforts. As polymer parts may be exposed to compressive or bending loads in their applications the different compression and tensile behavior should nevertheless be taken into account for optimized design.

The model of Schapery has been widely used to model the nonlinear viscoelastic behavior of polymers. Schapery (1969) introduced a procedure to determine model parameters from creep and creep recovery data. Step loading is assumed in order to obtain simple expressions for the model parameters, which may however lead to some error (Nordin & Varna, 2005). For

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http://dx.doi.org/10.1016/j.ijengsci.2012.05.004

use with arbitrary load histories, a parameter identification technique without restricting assumptions on the type of load history is needed. A general recursive strategy for solving the Schapery model equation has been developed for use in FE simulations (Henriksen, 1984). By using an improved algorithm of this type (Crochon, Schönherr, Li, & Lévesque, 2010) within a nonlinear optimization routine, model parameters can be determined by fitting the model to experimental data (Tscharnuter, Jerabek, Major, & Pinter, in press).

Numerous studies rely on 1d data and the Schapery model is taken in its 1d form. The model has been derived (Lévesque, Derrien, Baptiste, & Gilchrist, 2008) and applied (Nordin & Varna, 2005; Sawant & Muliana, 2008) in a 3d form, but its application is apparently somewhat limited by the unavailability of 3d data. This may be due to the difficulties of measuring the time-dependent lateral contraction (Tschoegl, Knauss, & Emri, 2002) in uniaxial long-term tests. Clip-on extensometer results are affected by local creep at the place of contact with the specimen and strain gauges introduce an erroneous time-dependence due to their own stiffness and viscoelasticity (Arzouminidis & Liechti, 2003). The aim of this paper is to examine the 3d Schapery model using uniaxial compression and tensile data. Digital image correlation is used for optical strain measurement to provide axial as well as transverse strains for a complete description of the stress–strain behavior. The paper is organized as follows. Section 2 summarizes the experimental procedures. In Section 3 the formulation of the model and the algorithm for solving the model equation are presented. Details on the finite-element implementation are also given. The optimization technique for the determination of parameters is introduced in Section 4. Results are finally presented in Section 5.

2. Experimental

2.1. Material

The investigated polyoxymethylene is Tenac 3010 produced by Asahi Kasei Corporation (Tokyo,Japan). ISO 3176 type B specimens were injection-molded.

2.2. Tensile tests

Tensile relaxation tests were performed with an electro-mechanical testing machine (Zwick Z250; Zwick-Roell, Ulm, Germany) equipped with a 10 kN load cell. For strain controlled tests an extensometer was used to control strain rate and applied strain. Axial and transverse strain were measured using the digital image correlation system ARAMIS (GOM mbH, Germany). Various aspects and details of this technique are discussed in reference (Jerabek, Major, & Lang, 2010). For this study, the measurement was performed in 3d mode using 105 mm lenses. The true longitudinal strain $\varepsilon_{t,l}$ and transverse strain $\varepsilon_{t,t}$ are calculated from the respective engineering strains, $\varepsilon_{e,l}$ and $\varepsilon_{e,t}$ by

$$\varepsilon_{t,l} = \ln(\varepsilon_{e,l} + 1) \tag{1}$$

and

$$\varepsilon_{t,t} = \ln(\varepsilon_{e,t} + 1) \tag{2}$$

The true stress is defined as

$$\sigma_t = \frac{F}{A_0}\frac{1}{(1+\varepsilon_{e,t})^2} \tag{3}$$

where F is the force and A_0 the cross-sectional area of the unstrained specimens.

2.3. Compression tests

Compression tests were carried out on an electro-mechanical testing machine (Instron 5500; Instron, Norwood, USA). The setup is based on a compression tool with highly accurate aligning bars and ball linings. It ensures a precise alignment of the polished compression plates and allows for the control of the axial strain by means off an LVDT mounted between the two compression plates. This setup is presented in detail elsewhere (Jerabek, Major, & Lang, 2010).

Compression specimens with a length of 10 mm were machined from the multipurpose specimens. The use of the multipurpose specimens limits the possible geometries for compression specimens but it ensures that the exact same material is used for tensile and compression tests. Before each test a preload of 10 N was applied before zeroing the LVDT to provide initial contact and PTFE spray was used to lubricate the compression plates to reduce friction. To avoid the cumbersome calibration procedure for 3d measurements in the confined space of the compression tool axial and transverse strain were measured with ARAMIS in 2d mode using telecentric lenses (S5LPJ0625, Sill Optics, Germany). Compared to standard lenses telecentric lenses are significantly less sensitive to out of plane-errors (Sutton, Yan, Tiwari, Schreier, & Orteu, 2008). Despite this, the obtained lateral strain was fairly high, giving Poisson's ratio values in excess of 0.5. The reasons for the erroneous transverse strain results have yet to be determined. Due to the limited number of compression specimens available, this could not be examined within this study. Two stress relaxation and two creep tests were done using a 3d setup with