



Finite-strain elasto-viscoplastic behavior of an epoxy resin: Experiments and modeling in the glassy regime



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ABSTRACT

The finite deformation response of an epoxy resin is investigated in the glassy regime using a constitutive relation that accounts for thermally activated yielding, pressure-sensitivity, strain softening and molecular chain reorientation. A previous formulation of this macro-molecular model is modified so as to decouple the onset of yielding from the peak nominal stress, and enable accurate modeling of temperature and strain-rate effects concurrently. The latter cannot be modeled adequately with existing models when the temperature dependence of elastic moduli is accounted for. Tension and compression experiments are carried out on Epon 862 across a range of temperatures and strain rates. Special care is taken to extract the intrinsic material behavior from the recorded mechanical responses using a new technique of video-based extensometry, which is well adapted to cylindrical geometries. Key features of the data include a temperature dependence of elastic moduli and a tension–compression asymmetry that goes beyond differences in peak yield. The experimental data is divided in two sets for model calibration and assessment. The first set contains sufficient data to identify all model parameters following a procedure outlined in the paper. The second data set is used to assess the predictive capabilities of the model for test conditions not used in the calibration step. It is shown that when the tension and compression cases are treated separately, with respect to post-peak softening, model predictions are excellent over the investigated ranges of temperature and strain rate.

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1. Introduction

Modeling the thermomechanical behavior of glassy polymers is a subject that has been tackled by many, see e.g., (Wu and Van der Giessen, 1993; Boyce and Arruda, 2000; Anand et al., 2009; van Breemen et al., 2011; Bouvard et al., 2013) and references therein. Seldom, however, is the identification of constitutive models based on discriminating experiments that include both tension and compression responses of the same material and for various strain rates and temperatures. In addition, most of the available data on polymers has been obtained on rectangular-prismatic specimens, which are notorious for promoting shear band formation and propagation. Under such circumstances, decoupling the intrinsic material behavior from structural and material instabilities becomes challenging. This paper deals with the identification of a physics-based constitutive model, hereafter referred to as macromolecular model, using new experiments. The latter consist

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of discriminating sets of data in tension and compression of cylindrical specimens over a range of temperatures and strain rates relevant to service conditions for composites used in jet engine fan containment cases.

Glassy polymers commonly exhibit complex mechanical behavior, which is time, temperature, rate and pressure dependent, e.g. (Hope et al., 1980; Klompen et al., 2005; Ames et al., 2009). Monotonic loading tests performed below the glass transition temperature result in stress–strain curves that display specific features. After an initial nonlinear regime, the flow stress reaches a peak. Most often follows a strain softening stage, the identification of which is complicated by specimen geometry effects. At large strains, a rehardening regime sets in, which is believed to be associated with molecular chain alignments. The characterization of the full range of the polymer response demands special precautions. For example, optical strain measurement methodologies can capture the full deformation range of polymers (G'Sell et al., 2002; Poulain et al., 2013) whereas some traditional characterization techniques, e.g. using strain gauges, promote early fracture due to stress concentrations (Buckley et al., 2001; Goldberg et al., 2005; Zhu et al., 2010).

In the past few decades, various constitutive models have been developed for polymers. Some models, often used to describe the behavior of epoxies, were formulated to account for pressure-sensitive yielding following Mohr–Coulomb or Drucker–Prager criteria. By construction, these models typically do not account for temperature and strain-rate effects observed in composites (Gilat et al., 2002) unless some viscoplastic formulation is adopted (Goldberg et al., 2005; Chowdhury et al., 2008; Ghorbel, 2008; Canal et al., 2009); also see (Voyiadjis et al., 2012) for alternative phenomenological models developed within continuum thermodynamics. Nevertheless, such models bear little connection to the fine scale macromolecular processes associated with polymer viscoplasticity. By way of contrast, constitutive relations are now widely available which account for thermally activated polymer segment motions and macromolecular chain orientations (Boyce and Arruda, 2000; Anand et al., 2009). Details aside, these models represent three-dimensional generalizations of the well known model of Haward and Thackray (1968). They have been developed mostly for amorphous thermoplastics but their potential for representing the behavior of thermosetting polymers has not been fully utilized so far; see e.g. (Srivastava et al., 2010). In addition to the inherent rate- and temperature-sensitivity, these formulations potentially allow for modeling material degradation, for example due to aging as it relates to macromolecular processes (Belbachir et al., 2010).

Thermosets share some characteristics that will define some important aspects of the constitutive model proposed in this paper. First, because of cross-linking they usually do not sustain the same strain levels as thermoplastics. We note in passing that their tensile ductility may be greater than believed so far on the basis of contact strain measurement techniques (Poulain et al., 2013). Second, there is a distinct nonlinear behavior prior to the peak nominal stress (Liang and Liechti, 1996; Poulain et al., 2013). Finally, the apparent elastic modulus E is dependent upon temperature T but not on strain rate within the ranges of interest (Cook et al., 1998; Behzadi and Jones, 2005; Littell et al., 2008; Jordan et al., 2008; Fleischhauer et al., 2012). The last two of these characteristics are common to many thermoplastics (Hasan and Boyce, 1995; Zairi et al., 2010) but are often disregarded in constitutive modeling. The nonlinear pre-peak hardening is not picked up by the constitutive models developed by Boyce et al. (1988), Arruda and Boyce (1993), and Wu and Van der Giessen (1993, 1996) who identify yielding with the peak stress. The same identification is made when viscoelastic effects are accounted for (Hasan and Boyce, 1995). This assumption leads to inconsistencies in the modeling of thermoplastics (e.g. see Fig. 10 in (Boyce et al., 1988)) and to much inaccuracy for representing the small strain plasticity of epoxies (Benzerga et al., 2009). Heuristic solutions to this problem have been proposed in the recent literature, e.g., (Ames et al., 2009; van Breemen et al., 2011; Fleischhauer et al., 2012). Most importantly, a temperature dependent elastic modulus $E(T)$ inevitably leads to a temperature dependent peak yield, within the context of the above models, since the athermal strength of the polymer scales with the modulus (Argon, 1973; Hasan and Boyce, 1995). In certain materials, the extent of the $E(T)$ dependence is such that it is impossible, quantitatively, to represent both the temperature sensitivity and strain-rate sensitivity of plastic flow using Argon's (Argon, 1973) viscoplastic law, which is an essential element of these theories. More recent attempts to use alternative viscoplastic laws by Mulliken and Boyce (2006), Richeton et al. (2006), Ames et al. (2009), and Bouvard et al. (2013) have focussed on the enhanced strain-rate sensitivity at high, impact-level strain rates or at very low temperatures. They are based on well documented transitions in molecular relaxation processes (Bauwens-Crowet et al., 1969; van Breemen et al., 2012). To our knowledge, the ability of the above models to reconcile the temperature dependent elastic moduli with thermally activated yielding in the low to moderate strain-rate regime has not been demonstrated.

In this paper, we use a modified macromolecular model to address the above mentioned issues in the context of an epoxy resin. The basis is a set of constitutive relations developed by Arruda and Boyce (1993) as extended by Wu and Van der Giessen (1993, 1996). The nonlinear pre-peak response is modeled after Chowdhury et al. (2008). When the temperature-dependence of elastic moduli is neglected the procedure for material parameter identification proposed by Boyce et al. (1988) and others works well. In particular, the minimal data set for identification may include data at fixed temperature and varying strain rates or vice versa. However, the identification procedure breaks down when the $E(T)$ dependence is not negligible. Therefore, a procedure aimed at material parameter identification is described in detail. Model calibration is carried out using a limited set of experimental data. Then the model predictive capabilities are illustrated for other test conditions not used for calibration.

To integrate the constitutive relations, we employ the same algorithms as in a recent three-dimensional finite-element implementation of the modified model by Kweon and Benzerga (2013) as an open source user-defined routine (UMAT) for the commercial code Abaqus. Finite deformations are accounted for using the additive decomposition of the rate of deformation, as in previous works (Wu and Van der Giessen, 1996; Tvergaard and Needleman, 2011; Chowdhury et al., 2008). One consequence of this choice is the use of hypoelasticity and, in the context of the UMAT, the use of a Jaumann rate. Obviously,

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