



Experimental investigation and modeling of the tension behavior of polycarbonate with temperature effects from low to high strain rates



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ABSTRACT

The effects of strain rate and temperature on the tension stress–strain responses of polycarbonate are experimentally investigated over a wide range of strain rates ($0.001\text{--}1700\text{ s}^{-1}$) and temperatures ($0\text{--}120\text{ }^{\circ}\text{C}$). A modified split Hopkinson tension bar is used for high-rate uniaxial tension tests. Experimental results indicate that the stress–strain responses of polycarbonate at high strain rates exhibit the nonlinear characteristics including the obvious yielding and strain softening. The tension behavior is strongly dependent on the strain rate and temperature. The values of yield stress and strain at yield present a dramatic increase at higher strain rates and decrease with the increase in temperature. Moreover, there exists a significant rate-sensitivity transition in the polycarbonate tension yield behavior. Based on the experimental investigation, a physically based three-dimensional elastoplastic constitutive model for the finite deformation of glassy polymers is used to characterize the rate-temperature dependent yield and post-yield behavior of polycarbonate when subjected to tension loading. The model results are shown close to the experimental data within the investigated strain-rate and temperature ranges.

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1. Introduction

Amorphous polymers have been extensively utilized as structural materials due to their excellent combination of mechanical property, production cost and weight. Polycarbonate can supply the good impact resistance as well as the transparency. Thus, it has a variety of engineering applications such as aircraft, automotive and security shielding components for impact protection. High strain rates are commonly encountered during the impact events such as projectile striking or blast loading and the polycarbonate will deform at high strain rates under the extreme temperature environments at actual usage. Consequently, an accurate understanding and modeling of the impact responses of polycarbonate at various temperatures is of great importance for scientific research and engineering structural design.

The split Hopkinson bar is an effective tool for investigating the dynamic behavior of materials at high strain rates (Gray, 2000). With the technical development of split Hopkinson pressure bar (SHPB) testing (Gray and Blumenthal, 2000), it becomes possible to evaluate the rate dependence of the stress–strain behavior of polymers at high strain rates up to 10^3 s^{-1} , which is two orders

of magnitude higher than those commonly performed under quasi-static and moderate strain-rate loadings from 10^{-4} to 10^1 s^{-1} . A great deal of attention has been given to the dynamic stress equilibrium, the constant strain-rate loading and the high signal-to-noise ratio of transmitted pulses for polymeric materials due to their properties of low density, stiffness and strength. Some experimental modifications such as the pulse shaping technique and the use of low-impedance aluminum, titanium or polymeric bars are proposed to perform the SHPB testing for low impedance polymers (Zhao et al., 1997; Chen et al., 2002; Zhao, 2003; Song and Chen, 2004; Khan and Farrokh, 2006). Also, the optimal specimen thickness and lubricant needs to be found to obtain correct response of polymers from SHPB experiments (Dioh et al., 1993; Cady et al., 2003; Trautmann et al., 2005). Numerous studies have investigated the effects of strain rate and temperature on the compressive behavior of polycarbonate (Rietsch and Bouette, 1990; Siviour et al., 2005; Mulliken and Boyce, 2006; Richeton et al., 2006; Omar et al., 2011). It is well known that polycarbonate exhibits an obvious elastic–plastic stress–strain behavior including linear elasticity, nonlinear elasticity, yielding, post-yield strain softening and strain hardening when subjected to high-rate compressive loading. Moreover, a dramatic increase of yield stress may be observed at high strain rates. Investigations on the relationship between the yield stress and logarithm strain rate in a wide strain-rate region indicate that there exists a transition

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threshold of rate sensitivity for yield behavior (Mulliken and Boyce, 2006), which is dependent on temperature (Richeton et al., 2006).

For the rate-dependent nonlinear elastic stress–strain behavior of polymers, an extensive number of rheological theories incorporating linear viscoelasticity and nonlinear viscoelasticity have been proposed in the differential or integral forms. The series and parallel connections of linear and nonlinear springs and dashpots are developed to describe the viscoelastic responses of polymers (Krempf and Khan, 2003; Ward and Sweeney, 2004; Khan et al., 2006; Shim and Mohr, 2011). Based on the widely accepted knowledge that the dominant mechanism during the plastic deformation of glassy polymers is a thermally activated process of molecular movements, analytical models are proposed for capturing the transition characteristic of yield behavior in the moderate strain-rate domain for strain rates less than 10^1 s^{-1} (Ree and Eyring, 1955; Bauwens-Crowet, 1973). For glassy polymers, the yield behavior is related to the two thermally activated processes, α and β , which are the primary factors dominated at low and high strain rates up to the rate in the order of 10^3 s^{-1} (Mulliken and Boyce, 2006). Furthermore, the modeling of yield-rate relation incorporating the temperature influence is extended over a wide range of temperatures across the glass transition to the rubbery state (Richeton et al., 2007). In the case of modeling the viscoplastic responses of glassy polymers, phenomenological models and physically based models have been introduced to describe the finite deformation behavior of glassy polymers (Boyce et al., 1988; Arruda and Boyce, 1993a; Wu and Van der Giessen, 1993; Arruda et al., 1995; Frank and Brockman, 2001; Anand and Gurtin, 2003; Wu and Buckley, 2004; Ghorbel, 2008). According to the concept that the plastic deformation is related to the macromolecular structure as well as the motion of the polymer segments and the alignment of the long-chain polymer molecules, Mulliken and Boyce (2006) developed an elastic–viscoplastic model by taking account of both α and β molecular processes to encompass high-rate compressive loading conditions. Following the thermodynamic framework and based on the principle of virtual power, Anand and co-workers developed the thermo-mechanically coupled theories to model the strain-rate and temperature dependent large-deformation responses of amorphous polymers in a temperature range which spans their glass transition temperature (Anand et al., 2009; Srivastava et al., 2010). Although differing in detail, the aforementioned elastic–viscoplastic constitutive models have the ability to predict the finite strain deformation including linear elasticity, yielding, post-yielding and thermo-mechanical coupling behavior of amorphous glassy polymers within a large strain-rate and temperature range.

Owing to the fact that there exist significant differences in tensile and compressive deformation behavior of polymers under high strain-rate loadings (Chen et al., 2002), it is therefore necessary to study the dynamic tension behavior of polycarbonate at various temperatures as a supplement of previous researches. In particular, tension tests can give us more deformation and damage information for glassy polymers such as crazing (Estevez et al., 2000; James et al., 2012) and necking (Li and Buckley, 2010; Uchida and Tada, 2011). However, due to the testing technique difficulty, very little research has been reported on the tension behavior of polymers at high strain rates (Cheng and Chen, 2003; Sarva and Boyce, 2007; Yin and Wang, 2010). The purpose of the present paper is to investigate the effects of strain rate and temperature on the tension responses of polycarbonate. A modified experimental technique based on the split Hopkinson tension bar (SHTB) was introduced to perform the high rate tension testing on polycarbonate at various temperatures. Experimental technique for detecting strain signals at a high signal-to-noise ratio was employed to capture the weak transmitted signal. The shape of the incident stress pulse was controlled in order to obtain the reliable stress–strain

responses. Based on the experimental investigation, a rate and temperature dependent elastoplastic constitutive model was extended to describe the strain-rate and temperature dependent tension stress–strain responses of polycarbonate.

2. Experimental details

2.1. Material

The material used in the present study was polycarbonate, purchased as extruded sheets (3 mm in thickness) of Lexan® MR10 from GE plastics. The mass density of polycarbonate is $1.2 \times 10^3 \text{ kg/m}^3$. The glass transition temperature is $140 \text{ }^\circ\text{C}$. Specimens were machined directly from sheet stock using a milling machine and then kept at room temperature for more than three days prior to testing.

2.2. High strain-rate uniaxial tension tests at different temperatures

High strain-rate tension tests at engineering strain rates of 10^2 – 10^3 s^{-1} were carried out using the split Hopkinson tension bar technique for obtaining the engineering stress – engineering strain relation of polycarbonate.

The technical differences between the SHTB and SHPB are the generation of the incident stress pulse and the specimen connection to the incident/transmitted bars. The SHTB setup used in the current study is schematically shown in Fig. 1 together with a Lagrange X – t diagram for illustrating the wave propagation in the bars. The pulse generating system includes a rotating disk with two pairs of impact hammers, an impact block, a prefixed metal bar and a connector. Also the top view of the pulse generating system is shown in Fig. 1. The incident stress pulse is initiated by the impact of the hammer fixed on the high-speed rotating disk on the impact block, which causes the prefixed metal bar connected to the block and the incident bar to deform until fracture. The amplitude of the incident stress pulse depends upon the diameter, d_p , of the prefixed metal bar. Correspondingly, a high diameter results in higher strain rates. The rise time and the duration of the incident stress pulse are dependent on the impact velocity and the length, l_p , of the prefixed metal bar. The maximum strain of the specimen is proportional to the duration of the incident stress pulse. The aim of this technique is to generate the incident stress pulse by making use of the plastic flow of prefixed metal bar and filter out the high-frequency components of the loading wave arising from the direct impact between the hammer and the block. The prefixed metal bar actually acts as a low pass filter and the oscillation in the incident pulse can be filtered a great deal.

The incident strain $\varepsilon_i(t)$, reflected strain $\varepsilon_r(t)$, and transmitted strain $\varepsilon_t(t)$ were recorded as functions of time t using strain gages G1 and G2 attached to the bars at two locations, respectively. According to the one-dimensional elastic stress wave theory (Zukas et al., 1982), the engineering stress, strain and strain rate in the specimen can be obtained from the strain gage measurements as:

$$\sigma_s(t) = \frac{P_1(t) + P_2(t)}{2A_s} = \frac{EA}{2A_s} [\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \quad (1)$$

$$\varepsilon_s(t) = \frac{u_1(t) - u_2(t)}{2} = \frac{C_0}{l_s} \int_0^t [\varepsilon_i(\tau) - \varepsilon_r(\tau) - \varepsilon_t(\tau)] d\tau \quad (2)$$

$$\dot{\varepsilon}_s(t) = \frac{C_0}{l_s} [\dot{\varepsilon}_i(t) - \dot{\varepsilon}_r(t) - \dot{\varepsilon}_t(t)] \quad (3)$$

where $P_1(t)$, $P_2(t)$ and $u_1(t)$, $u_2(t)$ are the forces and displacements on the right end of the incident bar and on the left end of the

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