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Influence of temperature and strain rate on the mechanical behavior of three amorphous polymers: Characterization and modeling of the compressive yield stress

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Abstract

Uniaxial compression stress–strain tests were carried out on three commercial amorphous polymers: polycarbonate (PC), polymethylmethacrylate (PMMA), and polyamideimide (PAI). The experiments were conducted under a wide range of temperatures (−40 °C to 180 °C) and strain rates (0.0001 s^{-1} up to 5000 s^{-1}). A modified split-Hopkinson pressure bar was used for high strain rate tests. Temperature and strain rate greatly influence the mechanical response of the three polymers. In particular, the yield stress is found to increase with decreasing temperature and with increasing strain rate. The experimental data for the compressive yield stress were modeled for a wide range of strain rates and temperatures according to a new formulation of the cooperative model based on a strain rate/temperature superposition principle. The modeling results of the cooperative model provide evidence on the secondary transition by linking the yield behavior to the energy associated to the β mechanical loss peak. The effect of hydrostatic pressure is also addressed from a modeling perspective.

Keywords: Yield stress; Mechanical response; PC; PMMA; PAI; Amorphous polymers; Strain rate effect; Temperature effect; Pressure effect; Experiments; Modeling

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1. Introduction

Strain rate and temperature are known to significantly influence the mechanical behavior of polymers. Since the beginning of polymer science, numerous experimental studies have been carried out on polymers to characterize the mechanical behavior as a function of temperature and strain rate. Among these studies, a great deal of attention has been given to the yield stress. Bauwens-Crowet, Bauwens and co-workers (Bauwens-Crowet et al., 1969, 1972; Bauwens, 1972; Bauwens-Crowet, 1973) have studied the yield stress of PC, PMMA and PVC as a function of temperature and strain rate. In their work, they correlated the yield behavior with molecular processes such as the secondary relaxation, but they did not study the flow stress for strain rates higher than 1 s^{-1}. In particular, to test materials under dynamic loading, one common technique employed is the split-Hopkinson pressure bar. The theory and practical application of the split-Hopkinson pressure bar testing method are clearly presented and reviewed by Gray (2000) in the ASM—Handbook, Volume 8 "Mechanical Testing and Evaluation". The specific use of the split-Hopkinson pressure bar for the evaluation of the high strain rate deformation of polymers and other soft materials is critiqued by Gray and Blumenthal (2000). The first work on the high rate response of plastics is due to Kolsky (1949) wherein he identified the importance of sample thickness on the measured response of the polymers. Walley et al. (1989) compiled reviews on the high strain rate studies of polymers, and they also showed that the strain hardening behavior of glassy polymers is dependent on the strain rate and temperature. Chou et al. (1973) analyzed the compressive behavior of several plastics and concluded that the temperature rise developed during deformation cannot be neglected. They also observed that the yield strength increases with increasing strain rate. Similar results for the flow stress were also found by Briscoe and Nosker (1985).

While numerous studies have investigated the influence of strain rate on the constitutive response for several polymers at room temperature, the influence of temperature at high strain rate has received much less attention. Among these studies, Rietsch and Bouette (1990) studied the compression yield stress of PC over a wide range of temperatures and strain rates, and revealed the importance of the secondary transition to account for the flow stress increases. Later, Chen et al. (2002) showed that the dynamic stress–strain behavior under tension differs significantly from the dynamic compressive response. Blumenthal et al. (2002) examined the influence of both strain rate and temperature on the deformation response of PMMA and PC, and more recently, Cady et al. (2003) studied the mechanical response of several polymers under dynamic loading at high temperatures.

The aim of this paper is first to present experimental results illustrating the effect of strain rate and temperature on the mechanical response for three amorphous polymers (PC, PMMA and PAI) under a wide range of strain rates and temperatures. Both PC and PMMA are very common commercial products widely used for their optical and mechanical properties; these materials are also used in extreme temperature and loading condition such as impact-resistant aircraft windows. PAI is a high technology molding polymer for reliable performance at extremely high temperature and stress. Among the technologically advanced applications of PAI, it can be mentioned that parts of the space shuttle, automotive transmission, and many other critical components are molded from this polymer. The testing of these three materials for a wide range of strain rates and temperatures is a required step to develop constitutive modeling able to accurately predict the mechanical behavior for severe applications. This is why the second objective of this article is to model the compressive yield stresses according to the new formulation of the Eyring cooperative model as proposed by Richeton et al. (2005). At the end, we discuss how the effect of hydrostatic pressure can be incorporated in the proposed model.