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Dissipation and resilience of elastomeric segmented copolymers under extreme strain rates

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ABSTRACT

The high strain rate behavior of elastomeric segmented copolymers has received significant attention in recent years in connection with the design of polymeric composites for a myriad of engineering and military applications. The presence of thermodynamically immiscible phases of hard and soft domains in these copolymeric materials enables multiple energy storage and dissipation pathways which offer new avenues towards highly resilient yet dissipative protective systems. In this research, the extreme strain rate behavior of an exemplar polyurea is addressed in Taylor impact tests to quantify ultrafast deformation processes at strain rates over 10^5/s which are incurred in ballistic and blast loading events. Numerical simulations of the high rate, inhomogeneous deformation incurred during Taylor impact tests are conducted using a recently proposed large deformation constitutive model implemented within nonlinear finite element simulations. The simulations show the predictive capability of the viscoelastic–viscoplastic constitutive model under extreme strain rate events and reveal the details of the evolution of the deformation and stress waves during impact loading. Additionally, the highly dissipative yet resilient features of polyurea under inhomogeneous deformation at extreme strain rates are elucidated in terms of energy dissipation and shape recovery by taking representative sets of constitutive models for rubbery and glassy polymers and their combinations. The remarkable ability of the polyurea to dissipate energy in a manner similar to a glassy thermoplastic yet exhibits the resilience of a rubbery material is shown in both the experiments and the models. This work reveals that the model of the two-phase structures of segmented copolymers is providing both dissipation and energy storage pathways under extreme deformation.

1. Introduction

Thermodynamic incompatibility in segmented copolymers often leads to a phase-separated morphology of hard and soft domains [1,2]. The phase-separated morphology enables hybrid mechanical performances of the constituents and can be tailored via a variety of pathways such as chemical composition, molecular dispersion, processing and synthesis [3–5]. The elastomeric segmented copolymers polyurea and polyurethane have been versatile materials for a myriad of engineering and military applications ranging from impact-protective coatings to self-healing microstructures via their unique mechanical, thermal and chemical properties [6–8]. The stress–strain behavior of polyurea and polyurethane over a wide range of strain rates reveals the highly dissipative yet resilient mechanical behavior under a variety of loading scenarios [9–13] and provides unique properties for protective composites under high strain rate events such as blast loading and ballistic penetration. Recent experimental and computational studies on polyurea–metal composites have investigated the effects of polyurea coatings on the protective performance of the sheet metals in terms of bi-layer separation and dynamic fracture [8,14–17]. In addition, a micromechanically-based viscoelastic–viscoplastic constitutive model was recently proposed to model the rate-dependent mechanical behavior of an exemplar copolymer polyurea by introducing two-phase micro-rheological mechanisms to account for the constitutive contribution from the hard and soft domains under a wide range of strain rates [18].

The Taylor impact test has been extensively utilized to study the high strain rate flow stress and constitutive behavior of metallic materials [19–23]. Although widely used on metallic and ceramic materials, relatively few studies on the Taylor impact behavior of

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polymeric materials have been reported. Briscoe and Hutchings employed Taylor impact tests to quantify the rate- and temperature-dependent flow stress of high density polyethylene (HDPE) [24]. Also, the Taylor impact behavior of polyetheretherketone (PEEK) was used to investigate dynamic failure behavior [25] and high strain rate mechanical properties [26]. A comprehensive work on Taylor impact testing of polycarbonate (PC) reported the mechanics of high strain rate behavior of glassy polymers by Sarva et al. [27] However, the study of extreme deformation behavior of elastomeric copolymers which possess hybrid properties of "glassy" and "rubbery" polymers has been largely unexplored at present. In this paper, the mechanics of extreme strain rate behavior of polyurea is elucidated in experiments and computational modeling using Taylor impact tests, where inhomogeneous dynamic deformation processes with ultrafast strain rates greater than 10^5/s are achieved. The highly resilient yet dissipative features of polyurea rods are examined under such extreme-rate events by quantifying evolution of characteristic geometries and localized deformation profiles. Finally, the "glassy" and "rubbery" features of elastomeric copolymers are discussed by comparing kinetic energy evolution and deformation profiles of the two-phase copolymer during Taylor impact to those of a purely hyperelastic rubber and those of a viscoplastic glassy polymer. This work provides a predictive framework to quantify the ultrafast deformation which can be incurred in realistic ballistic or blast loading events on this important class of copolymeric materials.

2. Review on mechanical behavior of copolymer polyurea

The thermodynamic incompatibility between the hard and soft domains of segmented copolymers leads to a phase-separated morphology of hard and soft domains. The hard segments are in a "glassy-like" state at ambient conditions while the soft segments are in a "rubbery-like" state, as indicated in dynamic mechanical analysis (DMA) in Fig. 1a. The two peaks in the loss factor represent distinct relaxation processes of the hard and soft domains of this polyurea, which lead to a transition in the rate-sensitivity in stress–strain curves. The stress–strain behavior at low to high strain rates is shown in Fig. 1b. As shown in Fig. 1c, the flow stress levels at true

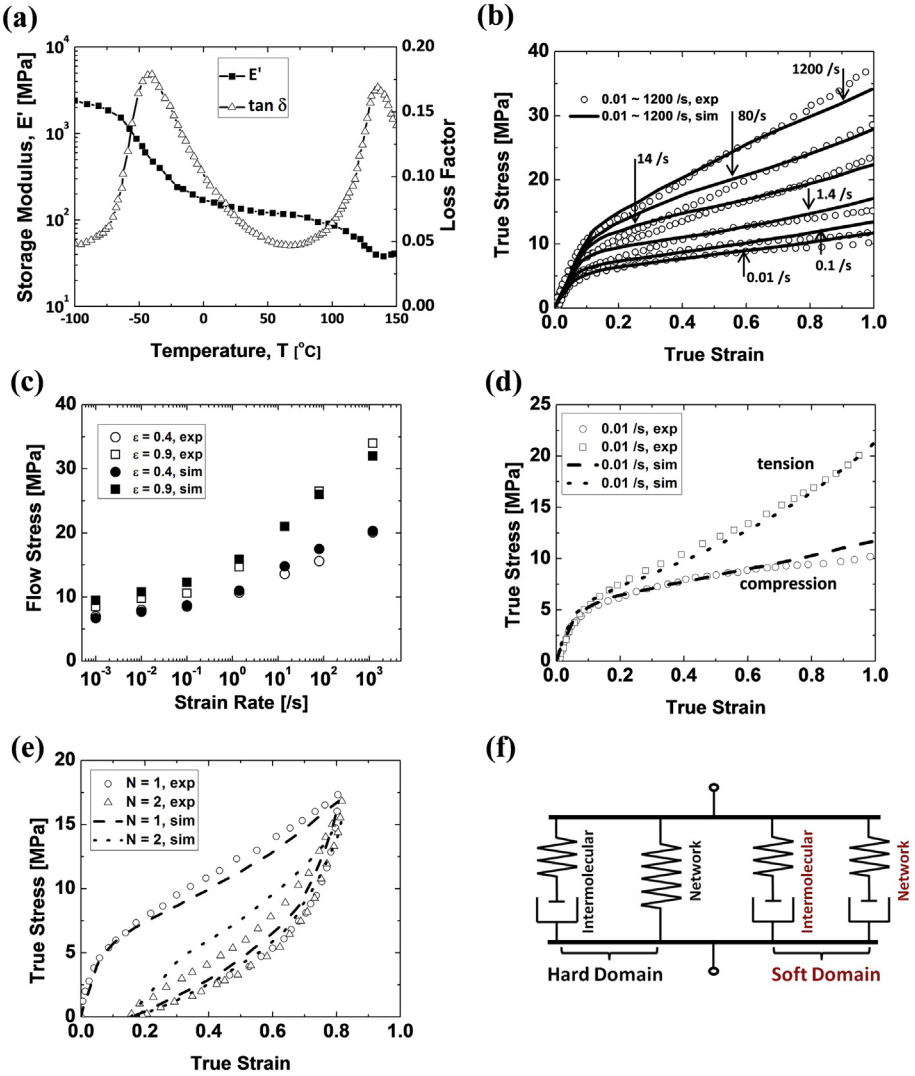

Fig. 1. Multiple relaxation processes explaining phase-separated morphology of polyurea, (a) dynamic mechanical analysis explaining a co-continuous microstructure with distinct relaxation processes of hard and soft domains, (b) stress–strain behavior under compression at low to high strain rate ranging from 0.01 to 1200/s (open symbols: experiments; solid lines: simulations), (c) flow stress at strains of 0.4 and 0.9 as a function of strain rates, (d) stress–strain behavior under tension and compression at a strain rate of 0.01/s, (e) stress–strain behavior under cyclic tension at a strain rate of 0.015/s, (f) schematic representation of multiple micro-rheological elements of hard and soft domains (stress–strain data from H. Cho et al. [18]).