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Effects of strain rate on mechanical properties of nanosilica/epoxy

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ABSTRACT

The mechanical properties (i.e., stress–strain relationship and peak stress) of nanosilica filled epoxies were studied using an Instron machine and a split Hopkinson pressure bar apparatus over a range of strain rates from 8×10^{-4} s^{-1} up to ~5×10^{3} s^{-1} under uniaxial compression. It was found that the nanosilica particles only reinforce epoxies slightly under both quasi-static and dynamic loading conditions. With a unit cell model, it was observed that owing to the existence of nanosilica, the surrounding strain field was changed and the strain-softening characteristics of the epoxy introduced a negative effect of the nanosilica particles as a reinforcement agent. That is, the particle strengthening effect depended on the mechanical characteristics of epoxy matrix. This was further confirmed by numerically simulating the mechanical behaviors of the composites for which (a) the matrix might assume different strain-softening or strain-hardening characteristics and (b) there were higher loadings of rigid silica particles.

1. Introduction

Engineering polymers have gained increasing popularity from industry for their good specific mechanical properties. To expand their applications, polymers are often incorporated with different fillers to improve their mechanical properties. The general availability of nano-sized fillers has offered an excellent chance to further increase the physical and mechanical properties of polymer matrices. Azeez et al. [1] reviewed research investigations conducted on epoxy/clay nanocomposites focusing on their morphology and the final mechanical and thermal properties due to the high intercalation chemistry and aspect ratio of nano-clay. The recovery performance and electrical properties of epoxy were enhanced with carbon fibers functionalized by grafting self-assembled graphene oxides [2], and the fracture toughness could be improved by achieving directional alignment of the carbon fibers [3]. Adding soft or rigid nanoparticles to epoxy enhances its fracture toughness. Liu et al. found that soft rubber nanoparticles can increase the fracture energy of epoxy more than hard nanosilica but at an expense of serious losses of Young's modulus [4] and tensile strength. Later, Lauke and Fu [5] conducted a comprehensive study on the fracture toughness improvements of polymers filled with hard inorganic particles from nano- to micro-sizes. Tang et al. [6] also added 10 and 20 wt.% nanosilica into epoxy to improve the transverse tensile strength, interlaminar shear and interlaminate fracture toughness of carbon fiber/epoxy laminates. Conradi et al. [7] showed that the elastic modulus and tensile strength could be increased at low fractions of nano-silica. Olmos et al. studied the thermo-mechanical properties of polysulfone filled with nanosilica particles, and found that the mechanical properties remain almost constant up to a relatively high loading (i.e., 5 wt.%) of nano-silica such as flexural strength and hardness [8]. Li et al. investigated the effect of nanoparticles of hyperbranched polyester and zirconium slag on impact toughness of epoxy matrix, and confirmed the toughening mechanisms which were induced by plastic deformation, inorganic nanoparticles and phase separation [9].

Materials and related integrated structures are sometimes subjected to explosive or impact loadings during their service, for example, bullet trains and helmets. The reliability of these structures depends on their mechanical properties under dynamic loading conditions. The split Hopkinson pressure bar (SHPB)

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technique is widely used to obtain the dynamic behavior of materials [10] and has indeed been adopted to examine the rate-dependent deformations of nanocomposites [11]. Thus, Song et al. [12] studied the compressive responses of alumina-filled epoxies under a wide strain-rate region, demonstrating a strong dependence on strain rate. However, the reinforcement mechanisms due to the particles have been little investigated. For polymers like epoxy, even reinforced by rigid particles, their stress–strain curves are quite similar to that of the neat polymer. That is, linear elastic deformation followed by a slight nonlinearity before reaching a peak stress; then strain-softening occurs with a plateau stress region prior to strain-hardening [11,12]. The peak stress is generally recognized as the *compressive yield strength* of the composite or polymer and is an important material property. Its dependence on strain rate and nanoparticle loading as well as the associated deformation mechanisms should be established for safe design with these epoxy nanocomposites.

The representative volume element (RVE) method is a useful tool to analyze the intrinsic deformation mechanisms of composites [13], especially for particulate composites. Based on a unit cell model, Li and Ramesh numerically studied the influence of particle volume characteristics on metal–matrix composites over a wide stain rate region, and found that rate-dependent flow stress is affected by particle aspect ratio and particle shape [14]. Since then, various unit cell methods were successfully employed to evaluate the thermomechanical behaviors of particle-modified composites such as ceramic-particle modified polymers [15], elastoplastic behavior of porous hierarchical scaffolds [16] and thermomechanical behavior of nanocomposites [17]. The RVE method is also used to investigate the particle size dependence of the elastic–plastic stress–strain response of polymer/clay nanocomposites [18]. Hence, the unit cell method is an effective way to study the reinforcement effect and even the underlying mechanism.

In this work, nanosilica particles with diameter of ~20 nm were selected to reinforce epoxy. Their mechanical characteristics under different loading rates were investigated in terms of the compressive yield strength, hereafter, called the *peak stress*. Based on unit cell modeling, the effects of the rigid nanosilica particles on epoxy and deformation characteristics were studied.

2. Materials and experiments

2.1. Material preparation

The resin was a standard diglycidyl ether of bisphenol A (DGEBA), and the spherical silica particles averaged ~20 nm with excellent dispersion in epoxy were supplied in master batches (Nanopox F400, nanoresins AG, Germany). The curing agent was a cycloaliphatic secondary amine, Piperidine, from Sigma–Aldrich. Four weight fractions of nanosilica particles were made: 0%, 2 wt.%, 6 wt.% and 10 wt.% nanosilica particles in epoxy (designated Epoxy, S2, S6 and S10). Fabrication details can be found in Ref. [4]. The fabricated materials were cut into cylindrical specimens with two sizes of ⌀5 mm × 5 mm and ⌀8.8 mm × 8.8 mm. The smaller size was used for quasi-static tests in an Instron machine; but both sizes were adopted for the split Hopkinson pressure bar tests. Before testing, all samples were annealed for 3 h at 80 °C to remove any residual stresses induced in the fabrication process.

2.2. Quasi-static experiments

The quasi-static tests were conducted with an Instron 5567 machine capable of recording the load and crosshead displacement automatically at two average true strain rate of ~8×10^{-4} s^{-1} and 3.2×10^{-2} s^{-1}. Before testing, vaseline was used to lubricate both end faces of a specimen to reduce the friction. This lubricating treatment was also applied to the split Hopkinson pressure bar tests.

2.3. Dynamic compression experiments

The split Hopkinson pressure bar was widely used to study the dynamic behavior of materials, especially for obtaining compressive stress–strain curves at high strain rates from 10^3 s^{-1} to 10^4 s^{-1} [10–12]. A split Hopkinson pressure apparatus consists basically of three bars: a striker bar, an incident bar and a transmitted bar as displayed in Fig. 1. The specimen was sandwiched between the incident and transmitted bars.

On testing, the striker bar was projected onto the incident bar by a gas gun and the specimen was compressed. The original voltage signals were recorded by the strain gauges through a Wheatstone bridge circuit. To obtain accurate measurements, the pulse shaper was attached to the impacting face of the incident bar to trim the incident wave to minimize the wave dispersion and maintain a constant true strain rate [19]. The signals obtained from a neat epoxy sample under a Hopkinson bar test were demonstrated in Fig. 2.

The voltage signals can be transformed into strain signal via the Wheatstone bridge formula. Based on the one-dimensional wave theory, the stress, strain and strain rate of the specimen can be calculated by Ref. [10]:

$$\begin{cases} \dot{\varepsilon}(t) = -\dfrac{2c_B}{l_s}\varepsilon_r \\ \varepsilon(t) = -\dfrac{2c_B}{l_s}\displaystyle\int_0^t \varepsilon_r dt \\ \sigma(t) = \dfrac{E_B A_B}{A_s}\varepsilon_t \end{cases} \tag{1}$$

where $c_B = \sqrt{E/\rho}$ is the longitudinal wave speed of the incident bar and transmitted bar in which ρ is the density of the Hopkinson bar, A_B and E_B are cross-sectional area and elastic modulus of the incident bar and transmitted bar, respectively, l_s and A_s are length and cross-sectional area of the specimen, and ε_r, ε_t are reflected strain signal and transmitted signal, respectively.

In this study, the Hopkinson bar apparatus with 15 mm in diameter was selected for different high strain rates. Different impact velocities of the striker bar were applied by controlling the pressure of the gas gun.

Experiments were repeated a minimum of three times under quasi-static and dynamic loading conditions for all nanosilica/epoxy composites. Fig. 3 plots the true stress–true strain curves of S2 for 3 repeated tests under a low (8×10^{-4} s^{-1}) and a high ($2.25–2.40$) $\times$ 10^3 s^{-1} strain rate. Clearly, these curves coincide each other indicating their repeatability and consistency. Two special characteristics are also noted in these curves: one is strain-softening after a peak stress and the other strain-hardening at large true strains.

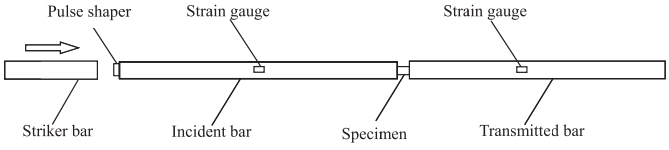

Fig. 1. Schematic drawing of Hopkinson bar test setup.