Materials and Design 59 (2014) 439–447

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

The effect of strain-rate on the tensile and compressive behavior of graphene reinforced epoxy/nanocomposites

Shahin Shadlou, Babak Ahmadi-Moghadam, Farid Taheri *

Department of Civil and Resource Engineering, Dalhousie University, 1360 Barrington Street, PO Box 15,000, Halifax, NS B3H 4R2, Canada

ARTICLE INFO

Article history:
Received 9 January 2014
Accepted 7 March 2014
Available online 16 March 2014

Keywords:
Strain rate
Graphene
Nanocomposite
Tensile
Halpin–Tsai model

ABSTRACT

The effect of strain rate on the mechanical behavior of epoxy reinforced with graphene nanoplatelets (GNPs) is investigated. Nanocomposites containing various amounts of GNP are prepared and tested at four different strain rates (0.01, 0.1, 1 and 10/s) under compressive and tensile loading regimes. The results show that incorporation of GNP highly affects the behavior of epoxy. The fracture surfaces of tensile specimens are also investigated using scanning electron microscopy (SEM) to discern the surface features and dispersion state of GNP. Finally, the predictive capability of some of the available models for evaluating the strength of nanocomposites are assessed and compared against the experimental results. Moreover, a modification factor to the widely used Halpin–Tsai model is proposed to improve the accuracy of the model when evaluating the Young's modulus of nanocomposites at various strain rates.

1. Introduction

A large number of studies have been carried out in past two decades to explore various aspects of nanocomposites reinforced with carbon nanotube (CNT) [1,2], carbon nanofiber (CNF) [3] and nanodiamond [4]. The recent discovery of graphene nanoplatelets as a new breed of carbon nanoparticle with its extraordinary physical properties, however, has led to generation of a new class of nanocomposites. In addition to the impressive thermal and electrical properties of GNP, the mechanical properties of the sp^2 bonding network in the GNP structure render them as suitable nanoparticles for enhancing the mechanical properties of polymers [5]. The recent advances in processing techniques has facilitated less costly and more environmentally friendly production of bulk GNPs [6], thereby increasing the potential of use of GNP based nanocomposites in various industrial applications. Chen and Lin [7] proposed an non-toxic, non-polluting and friendly to the environment for preparation process of GNP and obtained GNP with good structure and dispersibility.

Polymeric materials, either in the form of bulk or as adhesives, may be subjected to dynamic or impulse loading conditions. Strain rate has been known to affect the mechanical behavior of polymers quite significantly [8]; therefore, a deep understanding about the effect of strain rate on polymers properties is crucial in the design and safe in-service performance of polymeric structural components. The effects of strain rate and temperature on pure polymers and composites have been studied by several researchers [9]. Goglio et al. [10] investigated the dynamic mechanical response of two epoxy adhesives, in form of bulk materials, under tensile and compressive loadings exerted through a servo-hydraulic universal testing machine, as well as a tension–compression Hopkinson bar apparatus. However, their attempt for utilizing the Cowper–Symonds and Johnson–Cook models to fit their experimental data led to unacceptable results. Mcclung and Ruggles-Wrenn [11] studied the inelastic deformation response in polymerization of a high-temperature thermoset polymer. They observed that the influence of strain rate changed material's response during tensile loading and unloading and the strain recovery response. The material showed positive, non-linear strain rate sensitivity under monotonic loading. In addition, a nonlinear behavior was observed during unloading, regardless of the strain rate. They also reported that the strain recovery at zero stress is also highly affected by the strain rate. A few researchers have also investigated the effect of strain rate on composite materials. Jacob et al. [12] have provided a nice review on works conducted to investigate the strain rate dependency of mechanical properties of polymer composite materials.

While there have been several studies that have evaluated the effect of strain rate on pure polymers, there is a very limited number of studies on the effect of strain rate on polymers reinforced with nanoparticles. Among the available studies that have investigated the response of nanoparticle reinforced polymers under different strain rates, the emphasis has mainly

* Corresponding author. Tel.: +1 (902) 494 3935; fax: +1 (902) 484 6635.
E-mail address: farid.taheri@dal.ca (F. Taheri).

http://dx.doi.org/10.1016/j.matdes.2014.03.020
0261-3069/

been on organoclay [13]. For instance, Jo and Naguib [14] studied the tensile behavior of a high-density polyethylene/clay nanocomposite foam with different crystallinity. They found out that although the Young's modulus of the foams was improved by the increase in its crystallinity, the rate of improvement decreased at higher strain rates. They also proposed a viscoelastic stress–strain behavior for the foam. Moreover, Argento et al. [15] compared the loading rate effect on energy dissipation characteristics of bio-(sisal fiber) and nano-(nanoclay) cellular composite systems to conventional materials. Although they observed that the biocomposite systems showed unique energy dissipation characteristics and muted rate dependency (while the nanocomposite system did not), they could not identify the mechanism(s) that caused the trend. In another study, Shen et al. [16] indented the surfaces of a polymer/clay nanocomposite at different strain rates. They found that the strain rate had almost no effect on the elastic moduli of the neat or the nanocomposites system.

There have also been some strain rate studies on nanocomposites reinforced with CNT. Kakoee et al. [17] investigated the effect of CNTs on the mechanical properties of epoxy-based nanocomposites. They observed that addition of CNTs to epoxy led to degradation in the compressive young modulus and fracture energy of the nanocomposites. However, at higher strain rates, it was observed that the inclusion of CNTs increased the properties by 3% and 30.5%, respectively. The effect of strain rate on the response of syntactic nanocomposite foams was also studied by Al-Sharab et al. [18] by using the split-Hopkinson pressure bar, creating strain rates in the range 825–1670 1/s. They reported 20–40% increase in the apparent strength of nanocomposite at the higher strain rates. However, to the best of authors' knowledge, there has not been any research exploring the influence of rate effect on response of nanocomposites reinforced with GNPs.

In this study, therefore, the influence of various strain rates on the tensile and compressive responses of pure epoxy and GNP-reinforced epoxy nanocomposites is investigated. Nanocomposites with various GNP contents (i.e., 0.25, 0.5 and 1 wt%) are prepared and tested under strain rates of 0.01, 0.1, 1, 10/s. The fracture surfaces of the tensile specimens were investigated using the SEM micrographs. In addition, the capability of some of the available models for predicting the yield strength of the composite at different strain rates were assessed and compared against the results obtained experimentally. Moreover, a modification factor for the Halpin–Tsai model was proposed to improve the predictive accuracy of the model in regard to evaluating the Young's modulus of nanocomposites, with a particular emphasis on the strain rate.

2. Experiments

2.1. Materials and specimen preparation

Araldite LY 564 (Bisphenole-A) epoxy resin was used throughout this study along with Aradur 2954 (cycloaliphatic polyamine) hardener. This epoxy system is available through Huntsman Co. (West Point, GA). GNPs used for this research were supplied by XG Sciences (Lansing, MI). According to the supplier, they have an average thickness of 7 nm and a mean particle diameter of 25 μm. In order to prepare the specimens, the desired amount of GNPs (i.e. 0.25, 0.5 and 1 wt%) was added to the monomer and mixed using a mechanical stirrer for 15 min at 2000 rpm. To obtain a uniform dispersion of GNPs within the resin, the mixture was then processed using a three-roll mill homogenizer (Torrey Hill Technology, San Diego, CA). The milling cycles for the mixture containing 0.25, 0.5 and 1 wt% GNP were at 1, 2 and 4 cycles, respectively. Finally, the hardener was added into the mixture, and after degassing, the slurry was cast in the desired molds.

2.2. Mechanical characterization

The monotonic tensile tests were performed on coupons according to ASTM: D638 standard [19], except for those used for assessing the strain rates. The tensile tests were performed using an MTS servo-hydraulic test machine with a 100 kN load cell. A dynamic extensometer was also used to measure the displacement accurately. Cylindrical shaped specimens with a diameter of 8.5 mm and length of 9 mm were employed to assess the compressive properties, using an Instron servo-hydraulic test machine (model 8500) with a 25 kN load cell. The tests were performed at strain rates of 0.01, 0.1, 1, 10/s; thus appropriate cross-head displacements were chosen based upon the nature of test and dimension of each specimen.

2.3. Scanning electron microscope

A field emission scanning electron microscope, FE-SEM, (Hitachi S-4700, Dallas, TX) was used to investigate the fracture surfaces of the nanocomposites and neat epoxy specimens, as well as the status of GNP dispersion within the resin.

3. Results and discussion

3.1. Compression tests

Typical stress–strain curves for the neat epoxy and nanocomposites are depicted in Fig. 1. Only one curve for each case is presented to ease the comparison of the results. As can be seen, the Young's modulus and yield strength of the materials increased as the strain rate increased. The neat epoxy exhibited a similar response in all strain rates; a linear elastic response in the initial loading stage, followed by minor nonlinear behavior up to the yielding point, followed by an insignificant strain softening and subsequently exhibited a dramatic strain hardening. On the other hand, the behavior of nanocomposites is different to some extent. It appears that the nanocomposites underwent no strain softening, and that after the yielding point, they exhibited strain hardening.

The general trend for all nanocomposites containing different amounts of GNP is similar. The difference in strain hardening behavior of all materials at higher strain rates can be attributed to adiabatic heating effect, which has been reported to be significant at strain rate of 0.01/s or higher [20]. This effect seems to be more noticeable for nanocomposites, which might be due to higher thermal conductivity of these materials owing to inclusion of GNPs. It is also noteworthy to mention that flaws like agglomeration of GNPs, entrapped gasses and other defects would have influence in this portion of materials' response.

Fig. 2 presents a clearer comparison between the stress–strain curves of the neat epoxy and nanocomposites. While the fracture strain for pure epoxy is around 0.4 mm/mm, the value decreases to 0.3 in the case of nanocomposites, which signifies a transition from ductile to brittle behavior. However, a noticeable raise can be observed in the plastic flow of the nanocomposites compared to neat epoxy. The toughness of the neat epoxy and nanocomposites for strain rate of 0.01/s was evaluated by measuring the area under the corresponding stress–strain curve. The toughness value for the neat epoxy is 62 MPa and approximately 47 MPa for the nanocomposites. Nevertheless, if one assumes strain of 0.2 as the limiting strain for use of the materials as structural adhesives, then the toughness of the nanocomposites at this limit would be 1.5 times that of the neat epoxy.

In this study, the yield strength is defined as the pick value of the true stress as it transits from a linear variation to nonlinear one. The observed values of yield strength and Young's modulus