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Nonlinear constitutive equation for vapor-grown carbon nanofiber-reinforced SC-15 epoxy at different strain rate

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Abstract

In this study, tensile tests were performed on 0, 1, 2, and 3 wt% vapor-grown carbon nanofiber (CNF)-modified SC-15 epoxy at strain rates ranging from 0.00033 to 0.033 s^{-1}. Experiment results showed that both the elastic modulus and the tensile strength of the materials increased with higher strain rates, but the failure strain decreased with higher strain rates, indicating that the composite is a strain rate-dependent material. Experiment results also showed an even distribution of CNFs in the 1 and 2 wt% systems and an agglomeration of CNFs in the 3 wt% system. Therefore, the 2 wt% CNF-infusion system exhibited maximum enhancement, compared to other systems. Based on the results, a nonlinear constitutive equation was established to describe the strain rate-dependent stress–strain relationship of neat and nanophased epoxy. The parameters in this model are tensile modulus E, stress exponent n, and stress coefficient σ^*. The stress exponent n, which controls the strain rate-strengthening effect and the strain rate hardening effect of the composite, is independent of both strain rate and CNF content. The stress exponent σ^*, however, varies with both strain rate and CNF content.

Keywords: Strain rate; Tensile properties; Vapor-grown carbon nanofiber; Epoxy

1. Introduction

Epoxy resin has been important to the engineering community for many years. Epoxy-based materials provide outstanding mechanical, thermal, and electrical properties [1]. Using an additional phase, such as inorganic fillers, to strengthen the properties of epoxy resins has become a common practice [2]. These fillers have been proven to improve the material properties of epoxy resins. Because microscale fillers have successfully been synthesized with epoxy resin [3–6], nanoscaled materials are now being considered as filler material to produce high performance composite structures with further enhanced properties. Because of the improvements in mechanical, electrical, and chemical properties, many industries, including automotive, aerospace, electronics, and biotechnology [7,8] have become interested in nanocomposite materials.

Vapor-grown carbon nanofibers (CNFs), due to their high tensile strength, modulus, and relatively low cost, are drawing significant attention for their potential applications in nanoscale polymer reinforcement. They are synthesized through pyrolysis of hydrocarbons or carbon monoxide in the gaseous state in the presence of a catalyst [9,10]. Vapor-grown CNFs are different than other types of nanofibers, such as polyacylonitrile or mesophase pitch-based carbon fiber, in their method of production, physical properties, and structure. Thermoplastics, such as polypropylene [11–16], polycarbonate [17–21], and nylon [22]; thermosets, such as epoxy [23]; and thermoplastic elastomers, such as butadiene-styrene diblock copolymer [24] have been reinforced with carbon nanofibers.

Like many other polymer materials, the mechanical responses (deformation, strength, and failure) of nanofiber-modified epoxy, depend on the rate of deformation. It is necessary to know the mechanical behavior of a nanocomposite at different strain rates if a component made of the nanophased epoxy undergoes different loading speeds. The primary purpose of this paper is to describe the effects that different strain rates and the addition of vapor-grown CNFs have on the tensile behavior of epoxy. Based on the experiment results, a nonlinear constitutive equation was developed to describe strain rate-sensitive behavior of neat and nanophased epoxy.

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2. Materials and experiments

The resin used in this study is a commercially available SC-15 epoxy from Applied Poleramic, Inc. It is a low-viscosity, two-phased, toughened epoxy resin system consisting of part A (resin mixture of diglycidylether of bisphenol-A, aliphatic diglycidylether epoxy toughener) and part B (hardener mixture of cycloaliphatic amine and polyoxylalkylamine). The carbon nanofibers were obtained from Applied Science, Inc. The fiber diameters are in 60–200 nm and the fiber lengths range from 20 to 100 μm. The weight fractions of carbon nanofibers range from 0 to 3 wt% (corresponding to CNF volume fractions of 0, 0.63, 1.27, and 1.90%) to identify an optimal loading that gives the best thermal and mechanical properties.

Precalculated amounts of carbon nanofibers and part A were mixed together in a beaker. The materials were mixed using a high intensity ultrasonic irradiation (Ti-horn, 20 kHz Sonics Vibra Cell, Sonics Mandmaterials, Inc., USA) for 30 min on pulse mode (50 s on/25 s off). To avoid a temperature rise during the sonication process, the beaker containing the mixture was submerged in an ice bath. Once the irradiation was complete, part B was added to the modified part A and mixed using a high-speed mechanical stirrer for about 10 min. The ratio of part A to part B was 10:3. The rigorous mixing of part A and part B produced highly reactive, volatile vapor bubbles at initial stages of the reaction, which could detrimentally affect the final product by creating voids. A high vacuum was applied using the Brand Tech Vacuum system for about

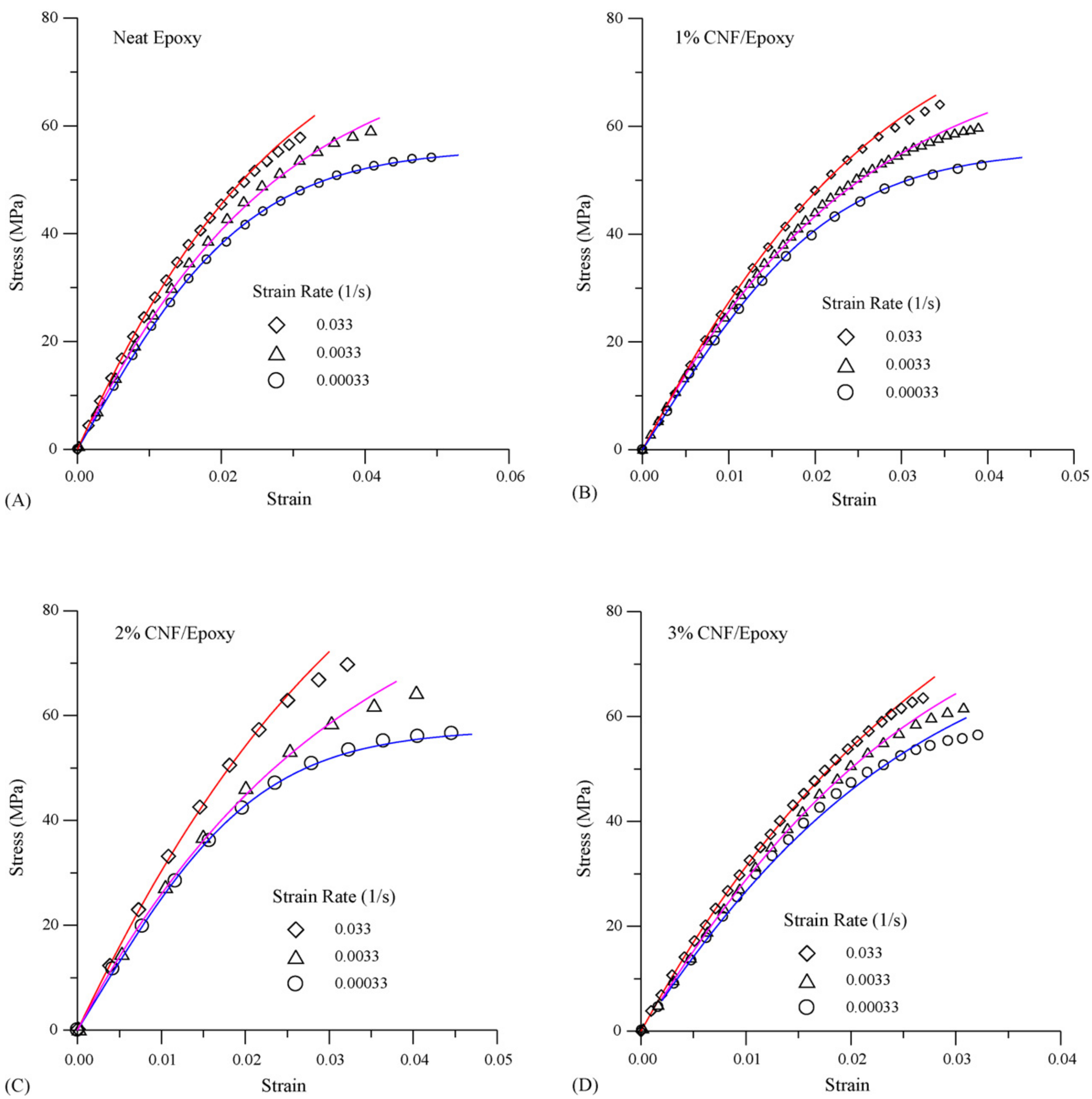

Fig. 1. Stress–strain curves of neat and CNF filled epoxy at different strain rate. (A) Neat epoxy; (B) 1 wt% CNF/epoxy; (C) 2 wt% CNF/epoxy; (D) 3 wt% CNF/epoxy).