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Extracting elastic modulus at different strain rates and temperatures from dynamic mechanical analysis data: A study on nanocomposites

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ABSTRACT

Viscoelastic nature of polymers makes their properties strongly dependent on temperature and strain rate. Characterization of material properties over a wide range of strain rates and temperatures requires an expensive and time consuming experimental campaign. While viscoelastic properties of materials are widely tested using dynamic mechanical analysis (DMA) method, the frequency dependent component of the measured properties is underutilized due to a lack of correlation between frequency, temperature, and strain rate. The present work develops a method that can extract elastic modulus over a range of strain rates and temperatures from the DMA data for nanocomposites. Carbon nanofiber (CNF) reinforced high-density polyethylene (HDPE) matrix nanocomposites are taken as the study material. Four different compositions of CNF/HDPE nanocomposites are tested using DMA from 40 to 120 °C at 1–100 Hz frequency. First, time-temperature superposition (TTS) principle is used to develop an extrapolation for the results beyond the test parameter range. Then the TTS curve is transformed to a time domain relaxation function using integral relations of viscoelasticity. Finally, the strain rate sensitive elastic modulus is extracted and extrapolated to room temperature. The transform results are validated with tensile test results and the error found to be below 13.4% in the strain rate range 10^{-5} to 10^{-3} for all four nanocomposites. Since the materials are tested with the aim of finding a correlation among the test methods, the quality of the material is not a study parameter and the transform should yield accurate results for any material regardless of composition and quality.

1. Introduction

Dynamical mechanical analysis (DMA) is a well established technique for the characterization of viscoelastic properties of materials under different loading frequencies and temperatures [1]. It has numerous practical applications such as determination of thermal transition temperatures, glass transition temperature (T_g) and polymer blend miscibility in the field of polymers [2–4]. Similarly, this technique has been used extensively to characterize composites [5,6] and biomaterials [7,8] for viscoelastic properties. In this technique, the storage modulus (E') and loss modulus (E'') could be calculated from the in-phase and out-of-phase components of stress and displacement cycles [9]. The E' provides a measure of energy stored in the material while E'' refers to the amount of energy dissipated in each cycle of the sinusoidal deformation [10]. Recent studies have expanded the utility of DMA technique to other application such as estimation of spatial distribution of material properties and crack healing [11,12]. However, both E' and E'' are in frequency domain and different from elastic modulus or secant modulus in time domain, which is a major limitation of applying DMA results to mechanical design. To use the results of DMA technique for time domain applications, a method needs to be developed to transform the frequency domain results to time domain.

Several works have reported the transformation from DMA measurements into time-domain response. Jia et al. [13] developed viscoelastic constitutive relations for polyurea and its composites using experiment results. Based on the master curves of E' and E'', continuous relaxation spectra are calculated and then the time-do-

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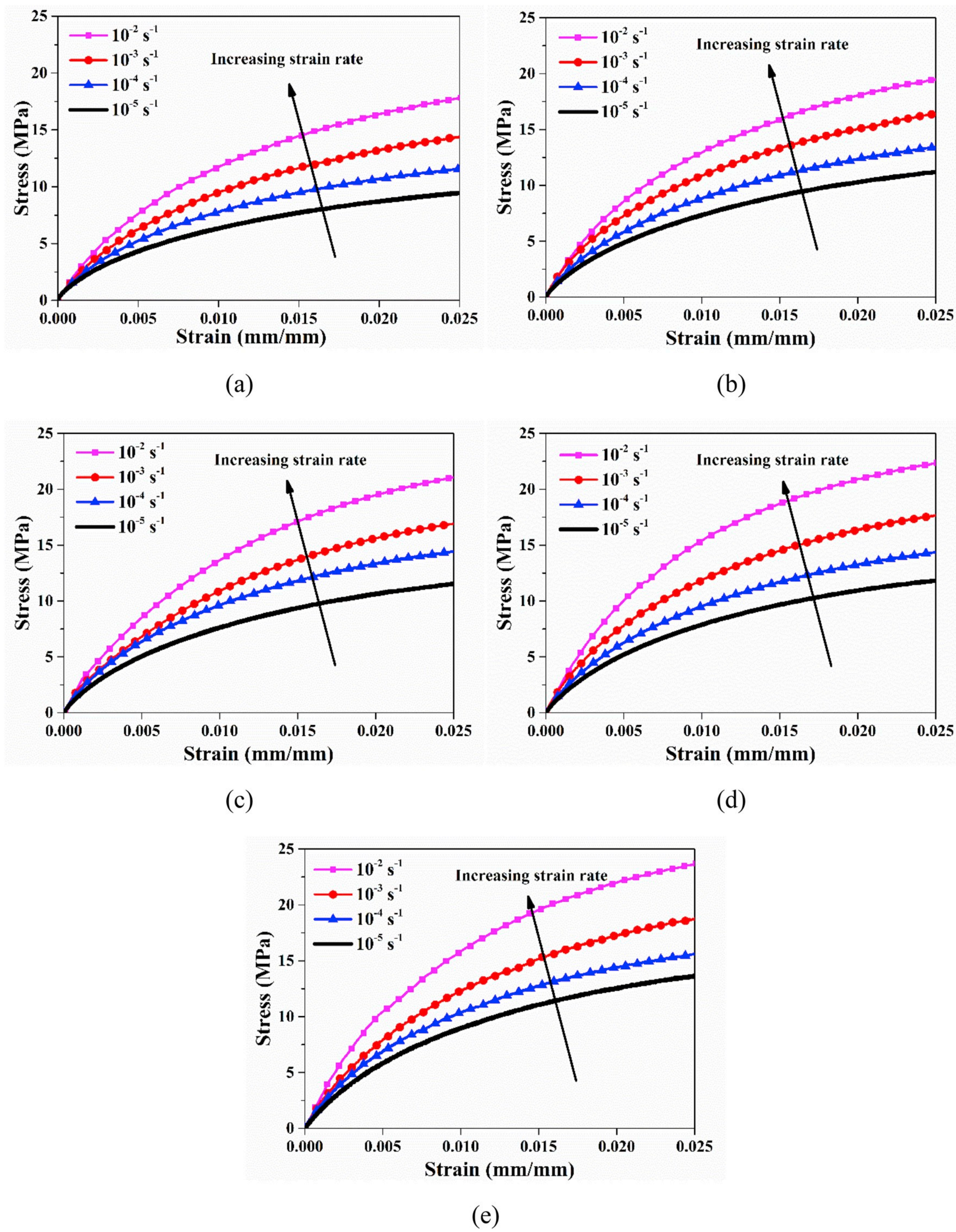

Fig. 1. A representative set of stress-strain curves for (a) neat HDPE resin and CNF/HDPE composites containing (b) 0.5 wt%, (c) 1.0 wt%, (d) 2.0 wt% and (e) 5.0 wt % CNFs.

main relaxation moduli are approximated. A transform has previously been developed to convert the frequency domain results obtained from DMA to time domain data and this method has been applied to neat polymers such as high density polyethylene (HDPE) [14], polycarbonate and vinyl ester resins [15]. The results showed that the predicted modulus closely matched with the tensile test results. Later, the same transform was also verified on hollow particle filled micro-composites called syntactic foams [16]. Compared to the tensile or compression testing for determining the elastic modulus over a range of strain rates and temperatures requiring testing a large