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Study of rate dependent behavior of glass/epoxy composites with nanofillers using non-contact strain measurement

Gurusideswar S.[a], Velmurugan R.[a,*], N.K. Gupta[b]

[a] *Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600 036, India*
[b] *Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi 110 016, India*

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ABSTRACT

The present research work discusses the effect of strain rate and clay on the dynamic tensile behavior of glass/epoxy composites. Nanocomposites of different clay content in terms of 1.5, 3 and 5 wt% are chosen for the study. Characterization of the nanoclay dispersed in epoxy system is investigated by X-ray Diffraction (XRD) and Fourier Transform Infra-red Spectroscopy (FT-IR), respectively. The non-contact Digital Image Correlation (DIC) technique is used for full-field strain measurement during dynamic loading using high speed CMOS camera. Stress-strain measurements are reported for glass/epoxy/clay nanocomposites over a wide range of strain rates from 0.001 to 450 s^{-1} and the variation of modulus, strength and strain to failure with strain rate are studied. A non-linear regression function is used to predict the tensile properties of glass/epoxy and its clay nanocomposites. The results show that the tensile strength and stiffness increase with increase in strain rate for neat glass/epoxy and its clay nanocomposites. An improvement in tensile modulus and strength is achieved with the addition of nanoclay. The fractography of tensile specimens is investigated using scanning electron microscopy (SEM) to discern the surface features and dispersion state of clay.

1. Introduction

Composite materials are widely used in aerospace structures, automotive industry, and marine structures, and in many instances they are subjected to high velocity dynamic loadings, which require prior knowledge of dynamic mechanical properties to prevent catastrophic failure at high loading rates. In addition, development of dynamic failure criteria and numerical simulations also require knowledge of material properties for different strain rates and most of the high strain rate studies were obtained from uniaxial compression testing. It is noted that the tensile tests can provide better knowledge on fracture and failure response of composites in contrast to the compression tests. Hence, understanding of stress-strain response of composite materials under tensile loading at high strain rates is necessary.

Many researchers have reported that glass/epoxy composites have shown increased tensile modulus and strength with the increase in strain rate [1–3]. Several techniques were developed to study the high strain rate effects of composites such as servo-hydraulic testing machine [4], expanding ring technique [5], split-Hopkinson pressure bar (SHPB) technique [6–8] and flying wedge apparatus [9]. Review literatures regarding the strain rate dependence of composite materials on mechanical properties were reported by Hamouda and Hashmi [10] and Jacob et al. [11]. However, it is found that the experimental techniques to determine the tensile properties of composites at the medium strain rates in the range of 1–100 s^{-1} are not well established [12].

The high end servo-hydraulic testing machine and the drop weight impact machine have been used to achieve medium strain rates, since the conventional servo-hydraulic machine is restricted to lower strain rates ($< 10\ s^{-1}$), due to its inertial effects of the load cell and grips. Lifshitz [13] studied the dynamic behavior of angle-ply glass/epoxy composites using an instrumented drop weight apparatus and failure stresses are found to be 20–30% higher than the static values; however failure strain and modulus are similar for static and dynamic loadings. Groves et al. [14] studied the strain rate effects between 0.0001 s^{-1} and 2660 s^{-1} for carbon fiber reinforced polymer composites and found an exponential-like increase in strength and modulus beyond strain rates of 10 s^{-1} due to high-intensity stress waves and they also observed changes in fracture propagation pattern. Barre and Chotard [15] studied the dynamic behavior of glass fiber reinforced phenolic and polyester resins and found that the modulus and strength tend to increase with strain rate. Okoli [16] conducted tensile, shear and 3-point bending tests to measure the energy absorbed until failure of a material using instrumented impact tester on glass/epoxy composites at strain rates ranging from 0.01 s^{-1} to 2.72 s^{-1}. They have found an increase in

* Corresponding author.
E-mail addresses: ramanv@iitm.ac.in, rvel@ae.iitm.ac.in (R. Velmurugan).

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tensile, shear, and flexural energy by 17, 5.9, and 8.5%, respectively, per decade increase in the log of strain rate. Pardo et al. [17] studied the tensile behavior of a glass/polyester composites for different strain rates and fiber orientations using hydraulic testing machine and found increase in tensile properties due to the strain rate effects. Shokrieh and Omidi [4] studied the behavior of glass fiber composites at strain rates of 0.001–100 s^{-1} using a servo-hydraulic testing apparatus equipped with a special jig and fixture. They found that increase in tensile strength, modulus, strain to failure and absorbed failure energy of about 52%, 12%, 10% and 53%, respectively and predicted those properties using non-linear regression function. Brown et al. [18] reported the strain rate effects on the tensile, shear and compression behavior of a glass/polypropylene composites over the strain rate range of 10^{-3}–10^{2} s^{-1} using an electro-mechanical universal testing machine and a modified instrumented falling weight drop tower with specially designed fixtures. The results showed that the tensile and compression modulus and strength increased with increasing strain rate. Li et al. [19] performed compressive and tensile dynamic characterizations of carbon composites using a drop weigh impact tester up to a strain rate of 100 s^{-1}. An increase of 32% in tensile modulus was observed when the strain rate changes from 3 s^{-1} to 18 s^{-1}. Shokrieh and co-workers [4,18] employed non-linear regression function to predict the tensile properties for different strain rates. Perogamvros et al. [20] developed a tensile testing apparatus using a drop tower to study the medium strain rate effects in the regime of 1–200 s^{-1} and also carried out the parametric FEM study for the validation of experimental results. They concluded that the drop tower setup could serve as a cost effective alternative to servo-hydraulic tensile equipment and also it is compatible with Digital Image Correlation optical devices. From the literature review, it is seen that the study of medium strain rate effect on glass/epoxy composites containing nanoclay is rather limited.

Addition of layered silicates or nanoclay [21–33] into the epoxy and fiber reinforced polymer composites have received much attention due to improvement in mechanical, thermal and electrical properties. This paper emphasizes the effect of clay on dynamic tensile loading of glass/epoxy nanocomposites using non-contact digital image correlation technique [34,35]. The application of DIC for SHPB experiments was already demonstrated by Gilat et al. [36] and Koerber et al. [37] to obtain strain field during dynamic loading.

Here, we present the study of dynamic tensile characterization of glass/epoxy/clay nanocomposites over a broad spectrum of strain rates from quasi-static to several hundred per second. Drop mass test setup is used for high strain rates and DIC has been used to obtain full/whole-field strain contours of the test specimen at high strain rates.

2. Experimental details

2.1. Materials

Epoxy, a medium viscous diglycidyl ether bisphenol A resin (DGEBA), with the curing agent, a low viscosity aliphatic polyamine (TETA) procured from Huntsman Ltd, (India) was used as a matrix material. E-glass fiber of woven type with 610 GSM was used as primary reinforcement. Organoclay, Garamite 1958® with a moisture content of 4% and a density of 1.7 g/cm^3 was procured from Southern Clay Products, Inc., (USA) and used as a secondary reinforcement.

2.2. Sample preparation

The glass/epoxy nanocomposites with various clay contents of 1.5, 3 and 5 wt% were fabricated using hand lay-up technique followed by compression molding process. The epoxy resin was preheated at 60 °C to lower the viscosity and organoclay was dried at 50 °C in the oven prior to mixing to remove moisture content. The clay was dispersed in epoxy resin using a mechanical stirrer at an optimal speed followed by an ultra-sonication process. An appropriate amount (12:100) of hardener was added to the epoxy/clay mixture and mixed well for 5 min. The final mixture was impregnated into the woven roving glass fiber mat with the assistance of hand roller to ensure that all fibers were uniformly wetted. After impregnation, the glass/epoxy/clay laminates were cured for 24 h at room temperature. Samples were cut by water jet cutting technique to get the required dimension of 10 mm gauge length × 3 mm width × 2 mm thick for high strain rate studies.

2.3. Characterization techniques

X-ray diffractograms were obtained by a PHILIPS PW-1730 diffractometer with CuKα radiation at a scan rate of 1°/min to study the dispersion of clay in epoxy. High Resolution Scanning Electron Microscopy (HR-SEM) studies were performed using a Hitachi S-4800 model, operating at 5 kV accelerating voltage to study the fracture surfaces of epoxy/clay nanocomposites. The surfaces were sputter-coated with a gold film prior to SEM investigation to avoid charging of epoxy samples. Fourier Transform Infrared Spectroscopy (FT-IR) was performed using PERKIN ELMER Spectrum one model at a scan range of 4000–450 cm^{-1} with 1 cm^{-1} resolution to characterize the organic/inorganic compounds of epoxy/clay nanocomposites.

2.4. Drop mass test setup

The drop mass test setup is employed for generating high strain rates from 0.001–450 s^{-1}. It consists of two guide rods, drop mass, and stop blocks. Prior to testing, drop mass is lifted by an electric motor to a pre-determined height through bearing assemblies and then dropped. The present test facility is custom-built to handle different specimen geometries as well as strain rates.

2.5. Digital image correlation

Digital image correlation is a non-contact strain measurement technique used to obtain the full-field displacement and strain contours of specimens. A random pattern (black speckle on white background) is sprayed on the specimen surface using aerosol spray paint. In the current study, a coarse speckle pattern is applied manually for dynamic testing, considering the image resolution of high

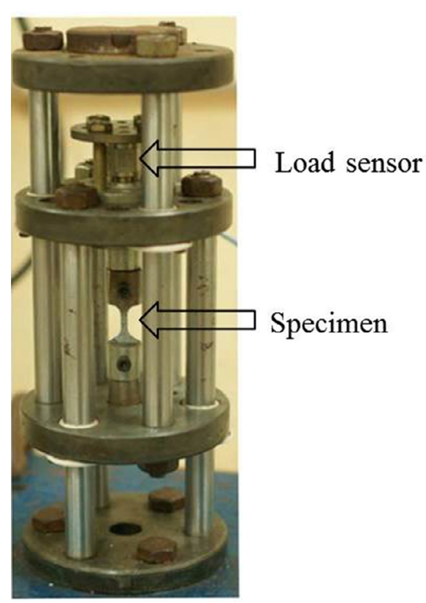

Fig. 1. Specimen fixture assembly.

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