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Effect of sonication on the mechanical response of graphene nanoplatelets/glass fabric/epoxy laminated nanocomposites

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ABSTRACT

This study focuses on the effect of sonication process time on the morphological characteristics of the graphene nanoplatelets (GNPs) and the mechanical performance of the produced GNPs/glass fabric/epoxy nanocomposites. Specifically, three different times, 20, 40 and 60 min, were tested. The rest of the sonication process parameters were kept constant, i.e. 100 W and 28 kHz. Both a scanning electron microscope (SEM) and an atomic force microscope (AFM) were used for the morphological investigation of the GNPs. Based on the microstructural investigations, the effect of the sonication time on the mechanical performance was explained and discussed.

1. Introduction

Graphene is a two-dimension atomic layer of sp^2-bonded C atoms which form a honeycomb arrangement [1–3]. Graphene is the base material for other nanoparticles, such as graphene nanoplatelets (GNPs), which are composed of several layers of graphene nanocrystals stacked together by Van der Waals forces though the (002) plane [4–6]. The graphene layer thickness in a GNP is usually ranging from 0.35 nm to 100 nm [7,8]. This 2-D material progressively attracts the interest of both the industry and the research society [9–11], due to the extraordinary properties it can provide when it is used as filler material in composites [6,12,13].

Graphene nanoplatelets are excellent fillers for polymer matrices [6,14–17] as regards several different enhancing properties. They can significantly improve the mechanical properties, such as Ultimate Tensile Strength, flexural strength and fracture toughness, of a matrix [6,14–16] and they can be used both alone as regular reinforcements [5,6,14] and together with other types of nanofillers to create hybrid composites in order to apply a synergy effect on the matrix [15,16]. Moreover, use of GNPs as filler material results in a great increase of thermal [18–20] and electrical properties [18,21–23].

The morphology of the embedded in a polymer matrix graphene nanoplatelets affects significantly the properties of the nanofillers and, consequently, the properties of the composite material [5,12]. The waviness of the GNPs surface strongly affects the electrical conductivity [24], as well as the thermal properties of the graphene nanoplatelets reinforced nanocomposite [20]. Since GNPs are of the newest graphene particles [6,25], very few studies have been conducted to investigate their effect on each different property of the composite matrix. However, for other carbon and graphene nanoparticles such as multi-walled carbon nanotubes, which are commercially available for more time, experimental studies have been carried out to investigate the effect of the nanoparticle morphology on the final mechanical properties of the nanocomposite [26,27]. The morphology of the nanofiller significantly affects the nanoparticle/matrix interface interaction [28–30] and, consequently, the deformation mechanism and the mechanical properties of the nanocomposite.

The morphological changes of a graphene nanoparticles are closely correlated with the dispersion method applied [5,9,11,28–30]. Of the most commonly used dispersion methods for graphene nanoparticles is the dispersion through sonication [5,9,28–30]. Two different forms of the sonication dispersion method are widely applied, the sonication bath and the probe sonication [26,31,32]. A sonication process modifies the graphene surface morphology, giving the graphene a more wrinkled form [5,9,33].

Recently, a few efforts have been made for new approaches on the structural modelling of nanomaterials. Specifically, Apuzzo et al. [34] investigated free vibrations of Bernoulli-Euler nano-beams by the stress-driven nonlocal integral model (SDM), in order to describe nonlocal phenomena in NEMS. A first gradient nonlocal model of bending for Timoshenko functionally graded nanobeams based on the Eringen model has been proposed by Barretta et al. [35]. Nonlocal integral constitutive laws, for application to nano-beams, have been investigated in a general setting by Romano et al. [36]. In this study, the

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strain-driven model and related local-nonlocal mixtures are addressed, with singular phenomena foreseen and numerically quantified. An approach which can be used to obtain other exact solutions for functionally graded Kirchhoff plates whose planform coincides with the cross-section of beams for which the Prandtl stress function known in an analytical form has been proposed by Apuzzo et al. [37]. A closed-form model for torsion of nanobeams with an enhanced nonlocal formulation has been provided by Apuzzo et al. [38] as well. A new nonlocal strategy for torsion of nano-beams has been provided by Barretta et al. [39]. Exact solutions of inflected functionally graded nano-beams in integral elasticity have been investigated by Barretta et al. [40] as well.

In the present study, the effect of different sonication bath process times on the mechanical properties of GNPs/glass fabric/epoxy nanocomposites has been investigated. Current research on this field lacks analytical studies on the relation between the morphological characteristics occurred from a pure sonication process (i.e. a sonication process which is not combined with other dispersion methods [5]) and the final mechanical properties of the produced nanocomposites. Additionally, one of the two most commonly used sonication processes, i.e. using a probe sonicator [5,9,28,29], cannot be easily applied on large scale productions. Therefore, the sonication bath dispersion method [26,31,32] was used for this study to facilitate the application of the results on such productions. Using a pure sonication bath dispersion method, this study focuses on the effect of sonication process time on the above described characteristics and properties. Specifically, three different times, 20, 40 and 60 min, were tested. The rest of the sonication process parameters were kept constant, i.e. 100 W and 28 kHz. The effect of the sonication time on the morphology of the graphene nanoplatelets was investigated using both a scanning electron microscope (SEM) and an atomic force microscope (AFM). Based on the microstructural investigations, the effect of the sonication time on the mechanical performance was explained and discussed.

2. Experimental procedure

2.1. Materials

The matrix material of the nanocomposite laminates was the low-viscosity Araldite GY 783 epoxy resin combined with the low-viscosity, phenol free, modified cycloaliphatic polyamine hardener Aradur 2965, both purchased from *Huntsman*. A Twill 2 × 2 (T2 × 2) E-glass fabrics of 280 g/m^2 density was used for matrix reinforcement. The fabric used as well as its orientations in the nanocomposite laminates can be seen in Fig. 1. The properties of the fabrics used can be found in Table 1. Graphene nanoplatelets (GNPs) of surface area (S.A.) 500 m^2/g, which were also used as filler material, were supplied by Alfa Aesar. The average graphene flake thickness within the structure of a GNP was 8–10 nm.

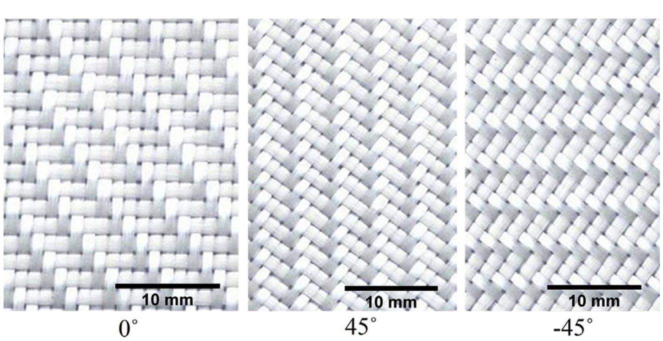

Fig. 1. The E-glass fabric in the orientations used for the stacking sequence of the laminated nanocomposite specimens, i.e. 0°, 45° and −45°.

Table 1
Properties of the fabrics used.

Fabric type	Twill 2 × 2	Uni-Directional
Filaments/yarn	1141	3230
Average yarn linear density	1.9 dtex – 1.66 denier	2.3 dtex – 2.03 denier

2.2. Preparation of GNPs/epoxy laminated nanocomposites

To ensure homogeneity of the suspension, weighed amounts of pre-dried graphene nanoplatelets were stirred gently into the epoxy resin (monomer) using a laboratory mixer. For the above mechanical stirring process, the speed was 200 rpm and the process time was 25 min [6]. Subsequently, the resin/GNPs mixture underwent different sonication bath processes [26,31,32]. One of the main parameters for all sonication processes is sonication time [31]. Therefore, three different process times were employed for sonication processes at 100 W and 28 kHz. Specifically, the sonication process times used were 20, 40 and 60 min.

After the sonication process was completed, the hardener was added in the mixture at the manufacturer recommended resin/hardener proportion, i.e. a weight ratio 2:1. A additional 5-min mechanical stirring process at 200 rpm was applied to the resin/GNPs/hardener mixture before it was used for the preparation of the specimens.

Five different GNPs w. t. contents, i.e. 1%, 2%, 3%, 4% and 5%, were used to produce the laminated nanocomposites. Nanocomposites of each GNPs content included specimens, the matrix mixture of which was produced using different sonication times, i.e. 20, 40 and 60 min. For each GNPs content, an additional specimen series without any sonication process applied was produced for comparison.

All specimens were manufactured using a hand lay-up procedure. The prepared matrix mixture was coated under constant stirring and hand-rolled on E-glass fabrics in layer sequence. Four E-glass fabric layers in $[0°/45°/\text{-}45°/0°]_T$ sequence were employed for each specimen. In order to achieve a 40 ± 1% by volume epoxy reinforcement in all specimens, both the fabric and the amount of resign used for coating were weighed before each hand lay-up process as well as after solidification [6].

The total size of each specimen which underwent 3-point bending tests was 126 × 12.7 × 1.3 mm, as in accordance with ASTM D790-03 test method. The dimensions of all the specimens which underwent tensile tests were 126 × 13 × 1.3 mm according to the ASTM D3039/3039 M standard test method. All specimens were cut at their testing dimensions using a Struers Discotom-2 along with a 40A25 cut-off wheel.

The evaluation of whether the use of tabs in the holding regions was necessary for the specimens which underwent tensile tests was carried out according to the aforementioned ASTM standard test method for tensile testing. The theoretical tab limits were marked on each specimen, see Fig. 2. If the failure occurs between the holding region and the theoretical tab limit, tab should be applied to all specimens. As can be seen in Fig. 2, since the breaks occurred in the control region (gage length), i.e. between the theoretical tab limits, no tabs were recommended from the standard test method.

After the hand lay-up process, each specimen was left to cure at ambient conditions for five days, according to manufacturer guidelines. Eight specimens of each GNPs content and of each sonication time were prepared and underwent each test (tensile and 3-point bending).

2.3. Experimental set-up and tests

An Instron 4482 test machine, the capacity of which was 100 kN, was used for the experiments. All tests, i.e. tensile and 3-point bending tests, were performed in the standard laboratory atmosphere of 23 ± 1 °C and 50 ± 5% relative humidity in accordance with ASTM D3039/3039 M and D790-03 test methods. Test conditioning was kept

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