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Short communication

Global and local nanofibrous interlayer toughened composites for higher in-plane strength

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ABSTRACT

Epoxy compatible P(St-co-GMA) copolymer based nanofibrous mats are introduced by electrospinning onto uni-directional (UD) and 0/90 twill weave carbon fiber/epoxy prepreg systems as interlayers. Anticipated in-plane strength improvement via higher matrix cracking resistance at the free edges, nanofibrous interlayered composites are verified by uni-axial tension tests on $(0)_6$ and $(0/90)_{6woven}$ laminates. The ultimate tensile strength of the $(0)_6$ laminates increased by 12%, whereas the tensile strength of the woven fabric composites increased by 18%. A localized interlayer reinforcing approach where the interlayers are incorporated at the vicinity of the hole is evaluated via open hole tension (OHT) tests of $(0/90)_{6woven}$ laminates. The OHT strength increased by 9%.

1. Introduction

Science and engineering of fiber reinforced advanced composite materials (FRC) is an actively broadening research field with increasing emphasis on their multi-phase and multi-scale characteristics. Emerging manufacturing and characterization techniques provide ability to manipulate materials at all scales from traditional macro scale to relatively recent nano-scale. The property tailoring by incorporating nano-scale constituents to change the macro-level behavior of composite materials is the focus of much research in the promising area of nanomaterials. For instance, the addition of nano or sub-micron fibrous interlayers for suppressing delamination of structural composites is a relatively new approach introduced by the Kim and Reneker [1] and Dzenis and Reneker [2,3]. Several other studies have followed this novel idea and demonstrated the capabilities of the electrospun nanofibers [4] and benefits from their incorporation into different composite systems [5,6]. These studies have shown that the polymeric nanofibrous interlayers are effective in the improvement of out of plane material properties. However, less attention was given to the failure behavior of these hybrid structures under in plane loading conditions. Given the early matrix cracking is one of the troublesome characteristics of laminated composites [7,8], under such loading conditions the ability of interlayers to resist transverse matrix cracking becomes interesting.

To exploit the idea that interlayer addition may suppress premature transverse matrix cracking (transverse to fiber direction) as well as delamination [9], our recent work first investigated the matrix compatibility with the electrospun P(St-co-GMA) based nanofibrous mats introduced as interlayer materials into conventional UD carbon/epoxy composite laminates. The out of plane behavior and toughness of laminates with interlayers were investigated by three point bending, end notched flexure and Charpy impact tests. Tensile tests transverse to the fiber direction on UD specimens were also reported to demonstrate the transverse strength increase resulting from the interlayers [10].

The present work compliments our previous studies by exploring the longitudinal (parallel to fiber direction) uni-axial tension behavior of UD laminates reinforced with nanofibrous interlayers. In addition, it extends the application of P(St-co-GMA) based interlayer reinforcements to woven carbon fabric/epoxy laminates and demonstrates their ability to improve in-plane strength for these laminates. Finally, the concept of "localized interlayer toughening of composite laminates" at stress concentration locations such as holes is introduced. Open hole tension tests (OHT) were conducted on tensile specimens where nanofibrous interlayer reinforcement is localized to the near-hole regions as opposed to integrating them over the whole interlaminar planes. Overall, the results support that P(St-co-GMA) nanofibers are strong candidates for toughening and strengthening of structural composites subjected to in plane loads as well.

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2. Experimental procedure

2.1. Specimen preparation and mechanical testing

Polymer synthesis, solution preparation and electrospinning parameters were as reported in our earlier work [10,11]. Polymer solution was electrospun directly onto prepreg layers. Two different carbon/epoxy prepreg systems from TCR composites were used: twill weave carbon fabric/UF3369 epoxy and UD carbon fiber/UF3325 epoxy. For un-notched tensile test specimens, the nanofibrous interlayers were electrospun on the whole surface of each ply where weight addition due to electrospun interlayers was only about 0.2%. The specimen dimensions and testing procedures were determined according to ASTM D3039. For open hole tension test specimens, the electrospinning was carried out onto the prepreg layers which were masked with a non-conducting and non-adherent plastic layer. As a result the electrospun nanofibers were only collected on the prepreg layers partially, at the intended area-the vicinity of to stress raisers (see Fig. 1a and b, the holes to be drilled after the consolidation of the source laminate for the OHT specimens) and the weight addition was considered none. The specimen dimensions and testing procedures were determined according to ASTM D5766. The hole diameter to width ratio is 1/6. Hence the open-hole tension test specimen had a 2.5 mm hole at the center and the interlayer toughened region was about 15×15 mm square centering the hole for each specimen.

For both tests, stack of 6 plies hosting 5 interlayers of electrospun nanofibers were prepared to form the final uncured composite laminates. The laminates were then vacuum bagged and cured at 100 °C for 24 h. The laminates were cut with a diamond disc cutter according to the specimen dimensions. Drilling of the center

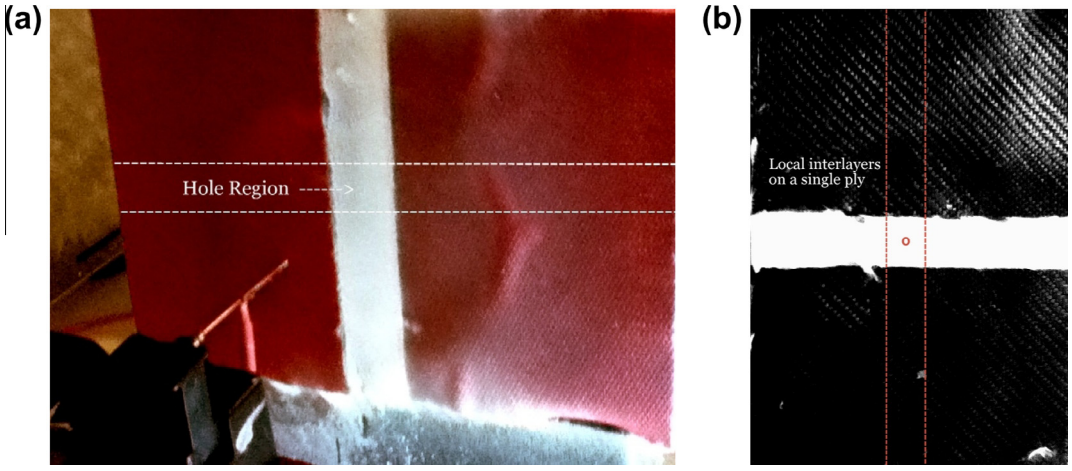

Fig. 1. (a) Electro-spinning with non-conductive mask for OHT specimen preparation. (b) Local interlayer addition over single prepreg ply. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

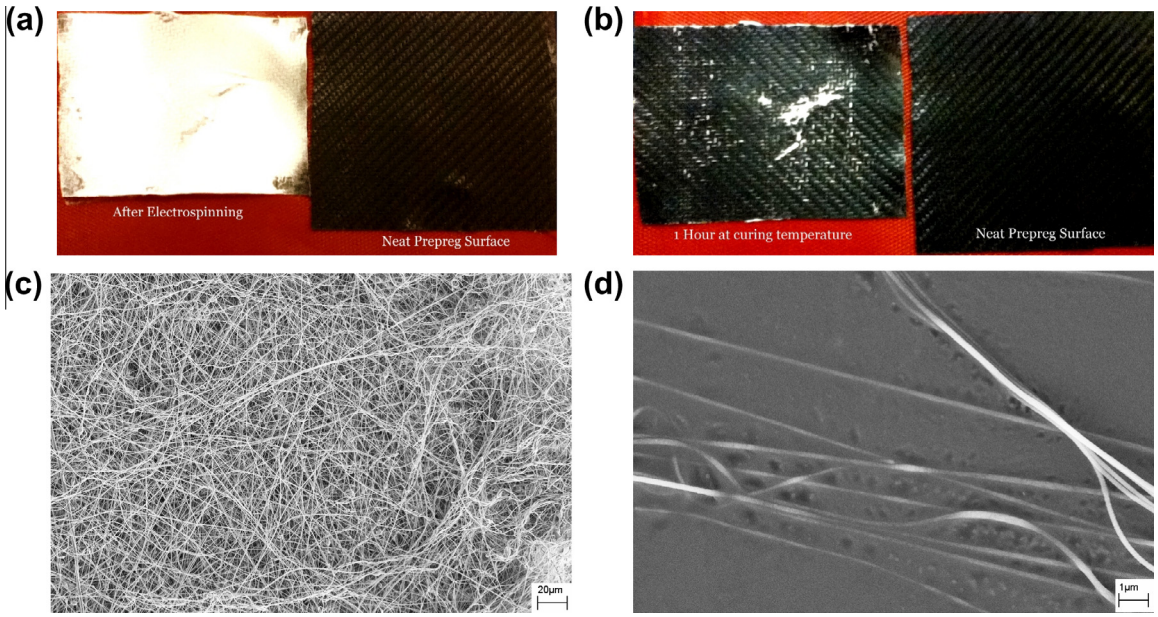

Fig. 2. Prepreg surfaces (a) just after electrospinning, at room temperature, (b) after 1 h hold at 100 °C, (c) nanofiber morphology on prepreg surfaces at room temperature and (d) nanofiber morphology on prepreg surfaces at 100 °C after 1 h hold. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)