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Electrospun Materials for Contrasting Delamination in Composites

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) laminates experienced a considerable diffusion in several application fields, especially where high specific mechanical properties are requested. While such materials are very versatile and contribute to obtaining lightweight and more "sustainable" structures, they potentially suffer from delamination, which poses an important limitation to their even more extensive widespread use. The integration of electrospun materials, especially nanofibers, is a smart solution to reduce such a phenomenon. The present work aims to compare different fibrous and nanofibrous systems that are able to contrast delamination by increasing interlaminar fracture toughness. In particular, the reinforcing effect delivered by electrospun veils made of Nylon 66, Nylon 66 coated with nitrile butadiene rubber (NBR), rubber-containing blends (NBR with polycaprolactone, PCL, or with Nomex), and a commercial thermosetting polymer is disclosed.

1 | Introduction

Laminate materials such as carbon fiber reinforced polymers (CFRPs) possess lightness and high specific mechanical properties. However, they may be severely damaged by impacts, promoting delamination and, thus, the catastrophic failure of structures and components [1].

The integration of electrospun materials, especially nanofibers, between prepreg layers is a smart solution to reduce such phenomenon [2]. The use of nanofibers made of polyamides and polyesters is common and has been investigated for years [3]. Instead, the integration of rubber-based nanofibers is recent (year 2020s) [4]. While rubbery nanofibers strongly increase delamination resistance, they may reduce other important thermomechanical properties of the modified laminate [5]. On the contrary, high-T_g nanofibers do not affect such laminate's properties, though they provide lower but significant toughening. The present work aims to present several fibrous and nanofibrous systems that are able to contrast delamination in laminated composites by increasing the interlaminar fracture toughness. The reinforcing effect delivered by Nylon 66, Nylon 66 coated with nitrile butadiene rubber (NBR), rubber-containing blends, and a commercial thermosetting polymer is disclosed. The integration of nanofibers allows for increasing the safety of structures and components and, in turn, also their sustainability.

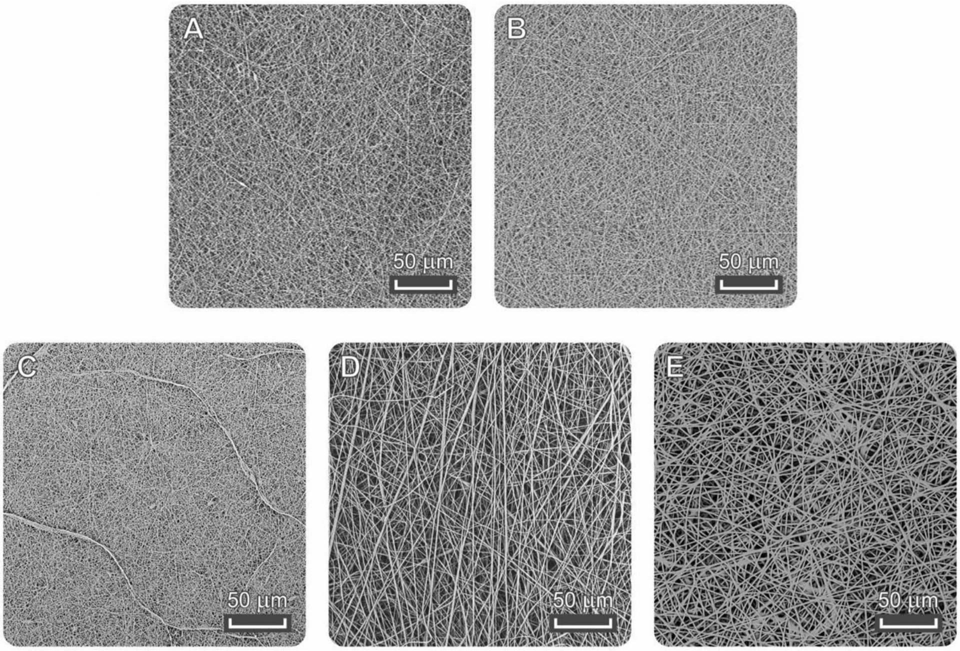

FIGURE 1 | Produced nanofibrous veils: (A) Nylon 66; (B) Nylon 66 coated with NBR; (C) NBR/PCL; (D) NBR/Nomex; (E) thermosetting/NBR blend.

2 | Materials and Methods

The nanofibers were produced via solution electrospinning of suitable solutions. A four-needle electrospinning machine (Lab Unit, Spinbow) equipped with 5 mL syringes and a drum as a collector (tangential speed 0.39 m/s) was used. Nylon 66 nanofibers were produced from a 10 wt% solution in a formic acid/$CHCl_3$ 1:1 wt solvent system [6]. The same nanofibers, coated with nitrile rubber (NBR), were produced by their impregnation with a 3% wt rubber solution [7]. Rubbery blend (NBR/PCL) or mixed (NBR/Nomex) nanofibers containing 60 wt% of NBR were produced according to procedures previously reported [8, 9]. The commercial epoxy-based thermosetting polymer was electrospun from a 35 wt% solution made of thermosetting polymer mixed with NBR (20 wt% with respect to the total polymeric amount) in DMAc/$CHCl_3$ 40:60 wt% solvent system. Electrospinning parameters: 0.4 mL/h flow rate, 22 kV electric potential, and 15 cm needle-to-collector distance. Electrospun materials were morphologically analysed through a benchtop SEM (Phenom ProX, PhenomWorld). Nanofibers were integrated into epoxy-based CFRP prepregs during the lamination step; the panels underwent curing in an autoclave (2 h at 135°C, 6 bar external pressure). Unmodified panels were also produced for the sake of comparison. Delamination resistance was evaluated in Mode I through double cantilever beam (DCB) tests, using a universal testing machine (Remet TC-10) at 3 mm/min speed rate.

3 | Results and Discussion

The nanofibrous mats were produced via single-needle electrospinning, even in the case of rubber-based nanofibers, i.e., NBR/PCL and NBR/Nomex ones, by electrospinning a stable solution blend and emulsion, respectively. The presence of the semicrystalline polymers is necessary to maintain the nanofibrous morphology over time, avoiding film formation due to the rubber cold flow of the uncrosslinked NBR. Even in the case of the commercial thermosetting epoxy-based polymer, the addition of NBR, together with a high solution concentration (35 wt%), is necessary to obtain a stable fibrous morphology over time. In the case of Nylon 66 + NBR nanofibers, the NBR dissolution is not compatible with the formic acid necessary to dissolve Nylon 66; thus the rubber was added by impregnating a preformed Nylon 66 nanofibrous mat with a suitable NBR solution and allowing the solvent to evaporate completely. Plain Nylon 66 nanofibers are among the most common nanofibrous membranes used to increase delamination resistance in composite laminates; thus, in the present study, they represent a benchmark. Figure 1 displays the produced electrospun veils.

Delamination tests in Mode I (opening) reveal the efficacy of nanofibrous mats interleaving to improve interlaminar fracture toughness, as evidenced by the G_I vs crack length reported in Figure 2. It is worth noticing that the nanofibers containing the NBR, regardless of how the rubber is inserted, provide better toughening with respect to the plain Nylon 66 nanofiber (2–3 times the reference, and up to near 5 times in the case of NBR/PCL modified CFRP). The use of the thermosetting-based fibers (1–1.2 µm) provides some enhancement in Mode I, comparable with the effect delivered by the sole polyamide nanofibers.

4 | Conclusion

The present work compares different nanofibrous and fibrous systems able to contrast delamination in epoxy-based CFRPs. Results reveal that the presence of uncrosslinked rubber delivered by the membranes can extremely boost the interlaminar fracture toughness, thus improving the safety and sustainability of the composite materials.

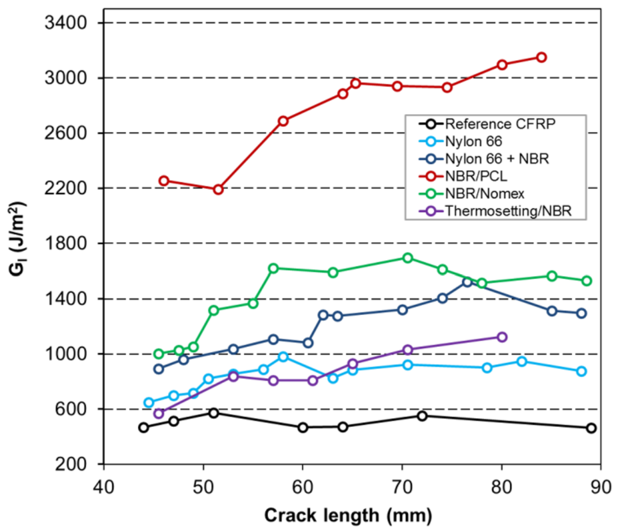

FIGURE 2 | Comparison of Mode I interlaminar fracture toughness of the nanomodified CFRP laminates and the unmodified one as a reference.

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Conflicts of Interest

The authors declare no conflicts of interest.

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